NEUTRINO 2024
XXXI International Conference on Neutrino Physics and Astrophysics
Milano (Italy) - June 16-22, 2024

Review of Diffuse SN Neutrino Background

Masayuki Harada
ICRR, University of Tokyo, Japan (mharada@km.icrr.u-tokyo.ac.jp)

NEUTRINO 2024 S10: Neutrino Cosmology, June 20th, 2024
@Milan, Italy

Contents

- Diffuse Supernova Neutrino Background (DSNB)
  - Introduction to DSNB
  - Importance of DSNB flux measurement
  - Current theoretical predictions of DSNB flux
- DSNB searches
  - Detection approach
  - Current status of DSNB searches and next-generation experiments
  - Latest Super-Kamiokande result with Gd

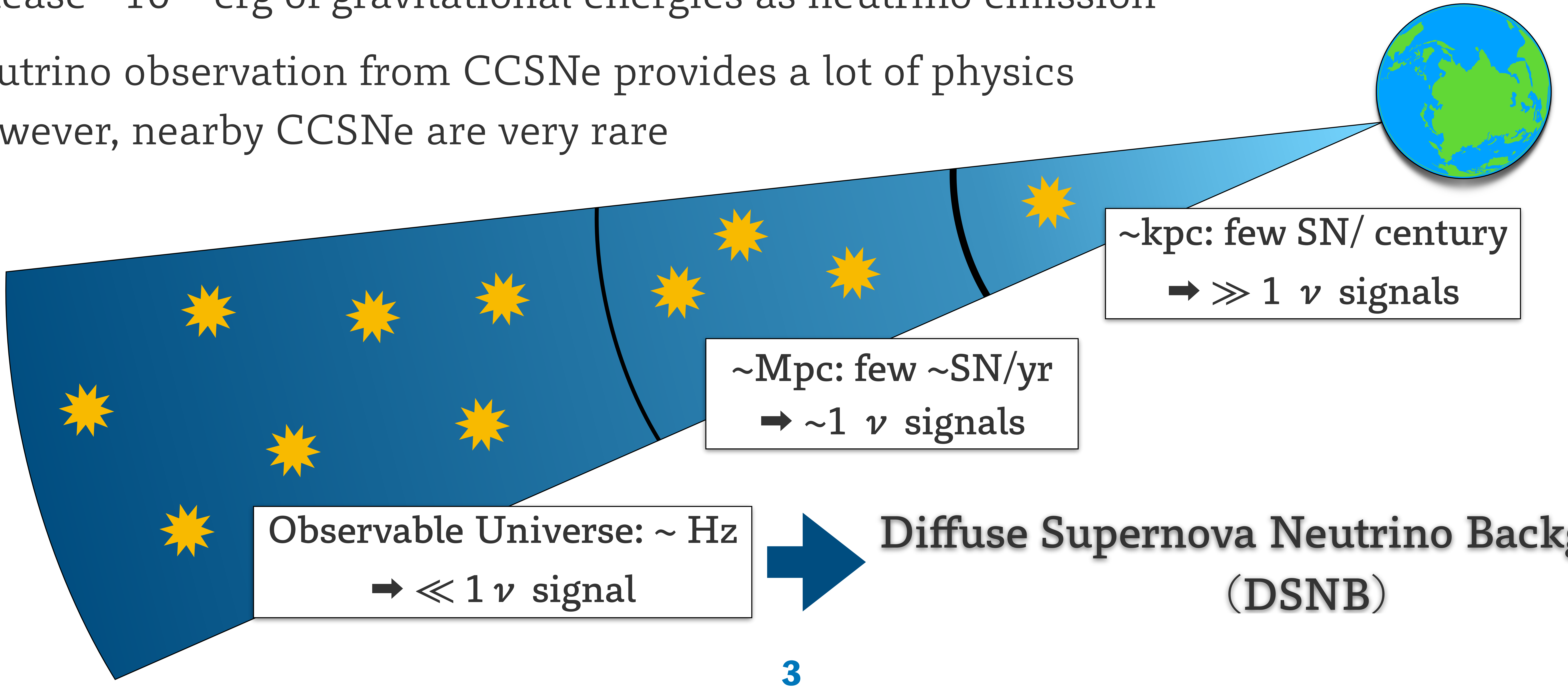
Neutrinos from Supernova

Source of Diffused Supernova Neutrino

Core-Collapse Supernova（CCSN）

- Release ~10^{53} erg of gravitational energies as neutrino emission
- Neutrino observation from CCSNe provides a lot of physics

However, nearby CCSNe are very rare



Diffuse Supernova Neutrino Background（DSNB）

DSNB : Physics insight

What information DSNB flux provide

- DSNB: “Relic” neutrinos from past all distant CCSNe

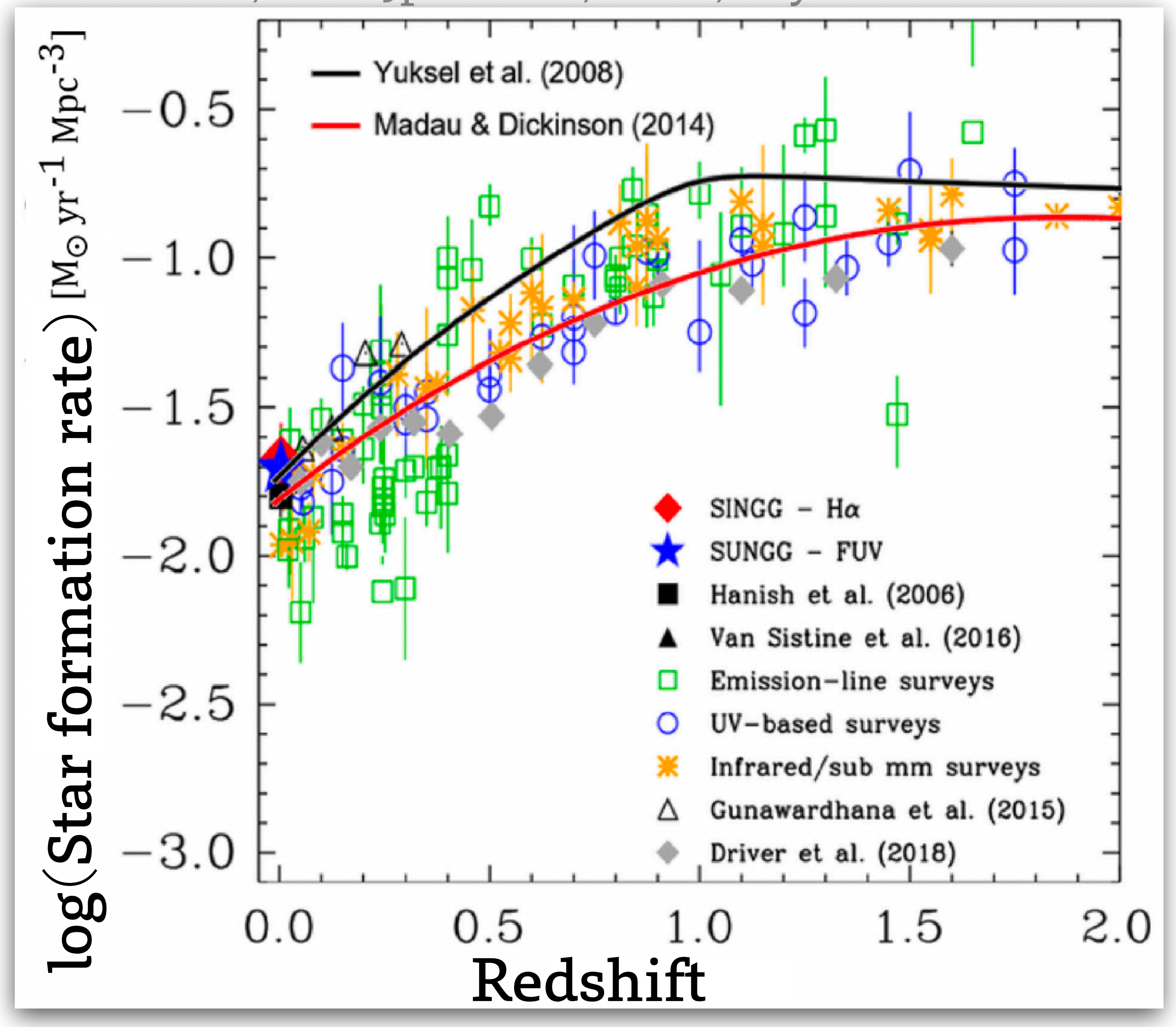
$$\Phi_{\mathrm{DSNB}}(E) \propto \int R_{\mathrm{SN}}(z) \frac{dF_{\bar{\nu}}(E,z)}{dE} \left|\frac{dt}{dz}\right| dz$$

$R_{\mathrm{SN}}(z)$ ∈ SN rate

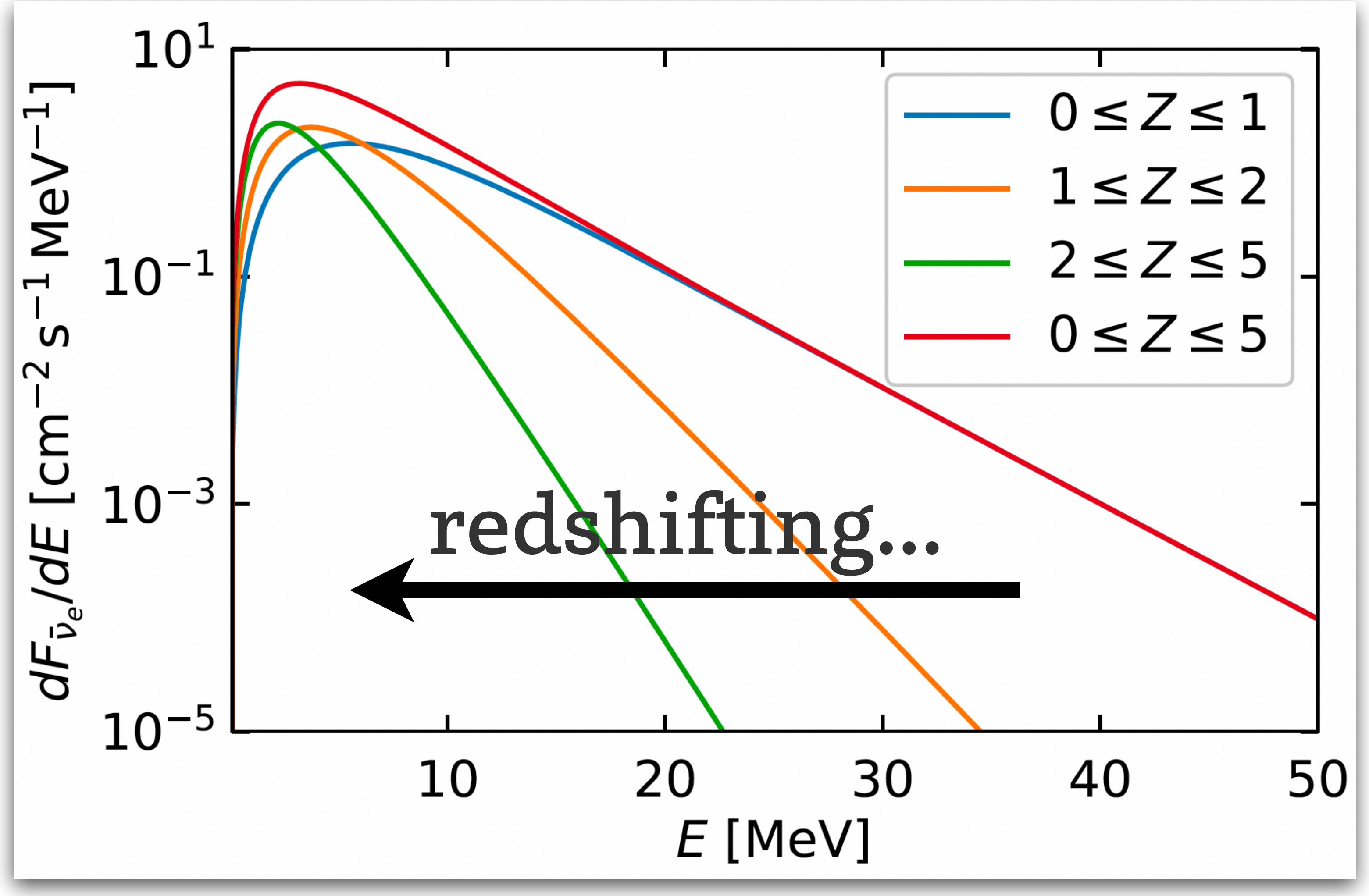
$\frac{dF_{\bar{\nu}}(E,z)}{dE}$ ∈ SN ν emission

$\left|\frac{dt}{dz}\right|$: ΛCDM, cosmic expansion

S.Ando et al., Proc. Jpn. Acad., Ser. B, Phys. 99 (2023) 10



S.Ando et al., Proc. Jpn. Acad., Ser. B, Phys. 99 (2023) 10



Various effect depending on the redshift (z) contribute DSNB flux

DSNB: flux prediction

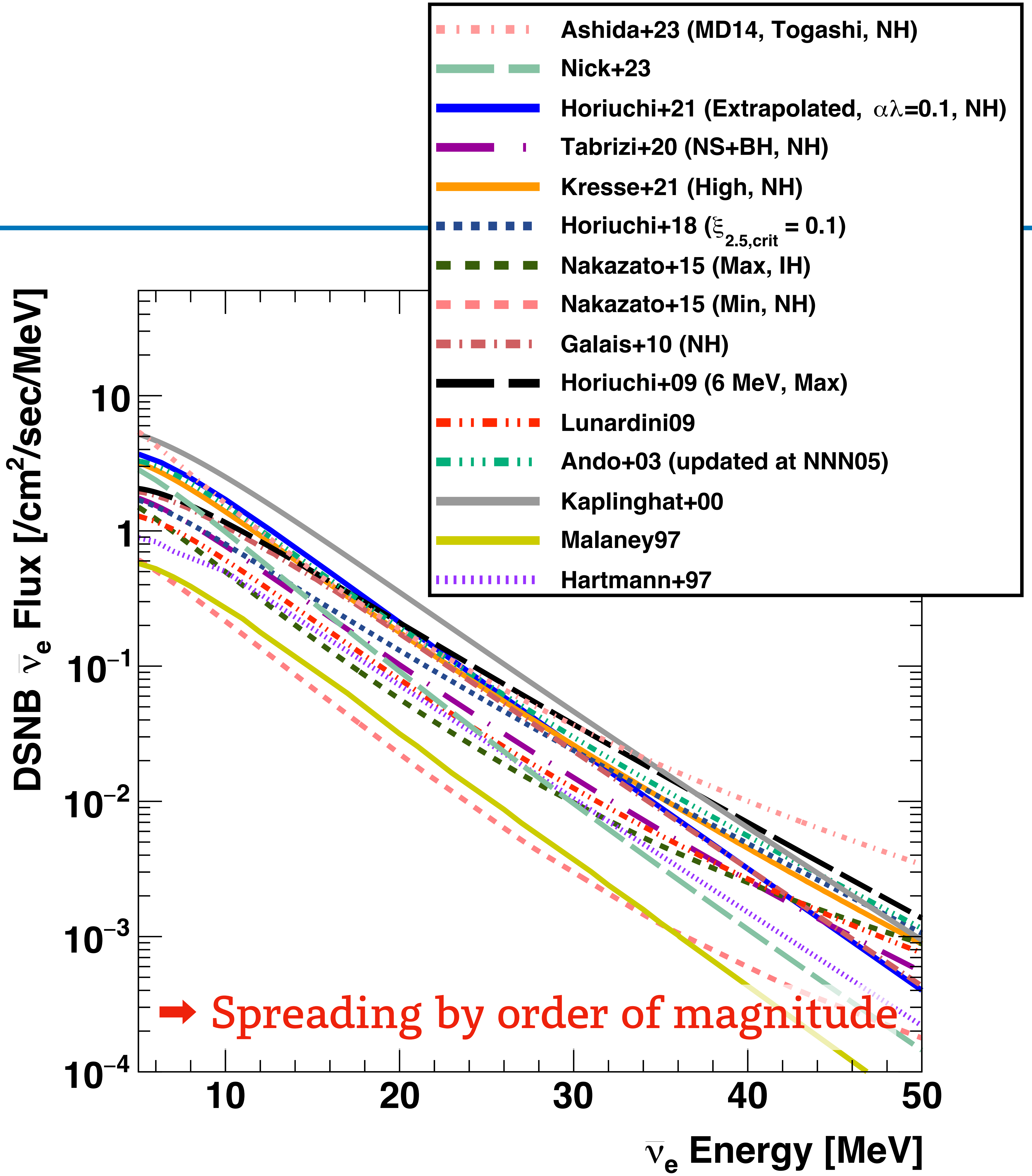
What information DSNB flux provide

SN rate

- Depends on the star formation history
  - Star formation rate
  - Failed CCSNe rate; BH formation rate
  - Binary star formation effect

SN ν emission

- Flux is averaged due to integration, However…
  - Typical CCSN neutrino spectrum
  - Neutrino oscillation inside the star
  - Neutrino decay, and other NSI



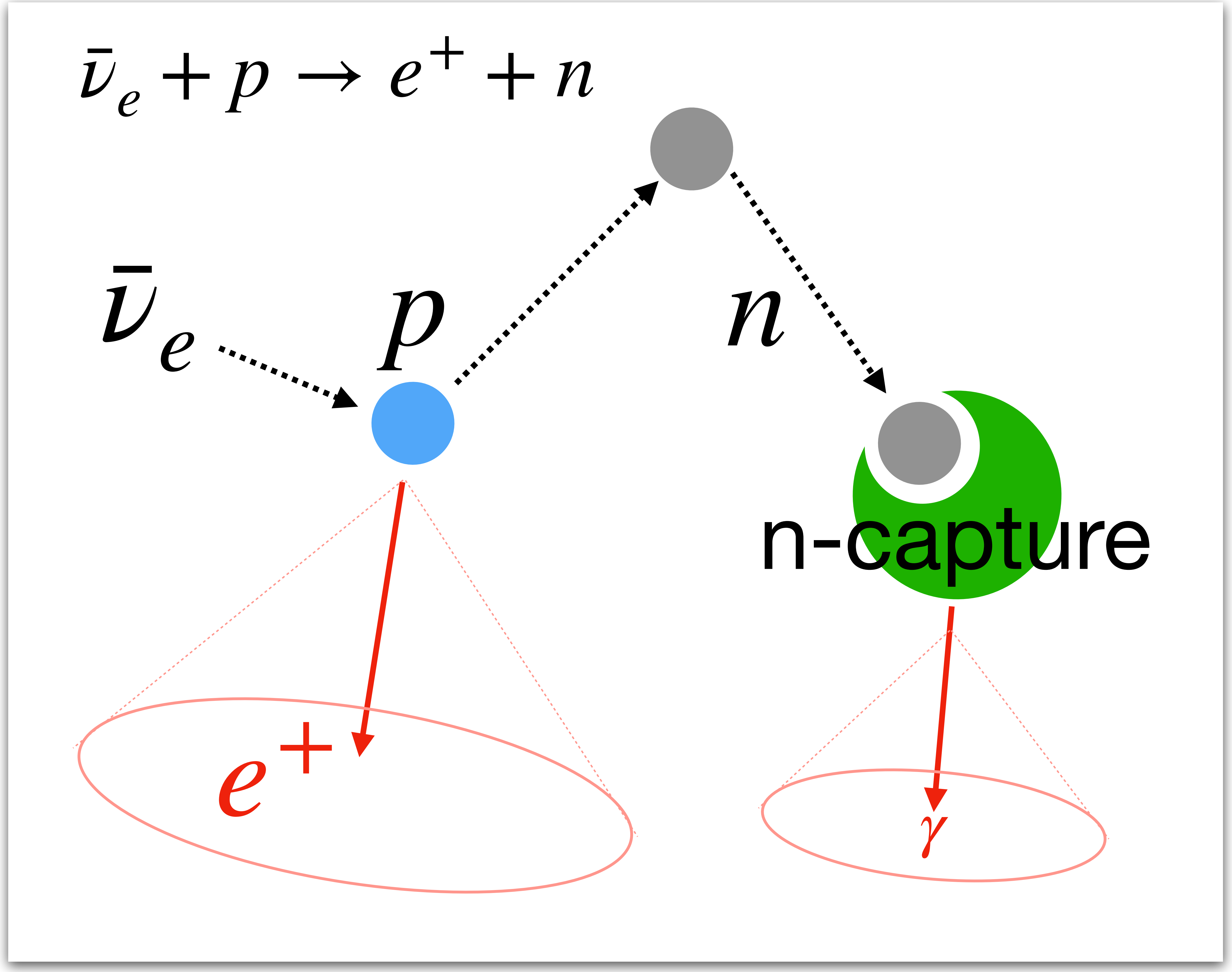
DSNB: Detection

How we can detect DSNB

Detection channel

- Inverse beta decay (IBD): $\bar{\nu}_e + p \rightarrow e^+ + n$
  - Large cross-section in DSNB energy region
  - Simple topology with one e+ and n
    ➡ **Coincidence detection reduces enormous background**

- Expected event rate: 0.13 event /kton/yr
  ➡ Large volume and high background reduction is required to search DSNB due to its low event rate



DSNB searches

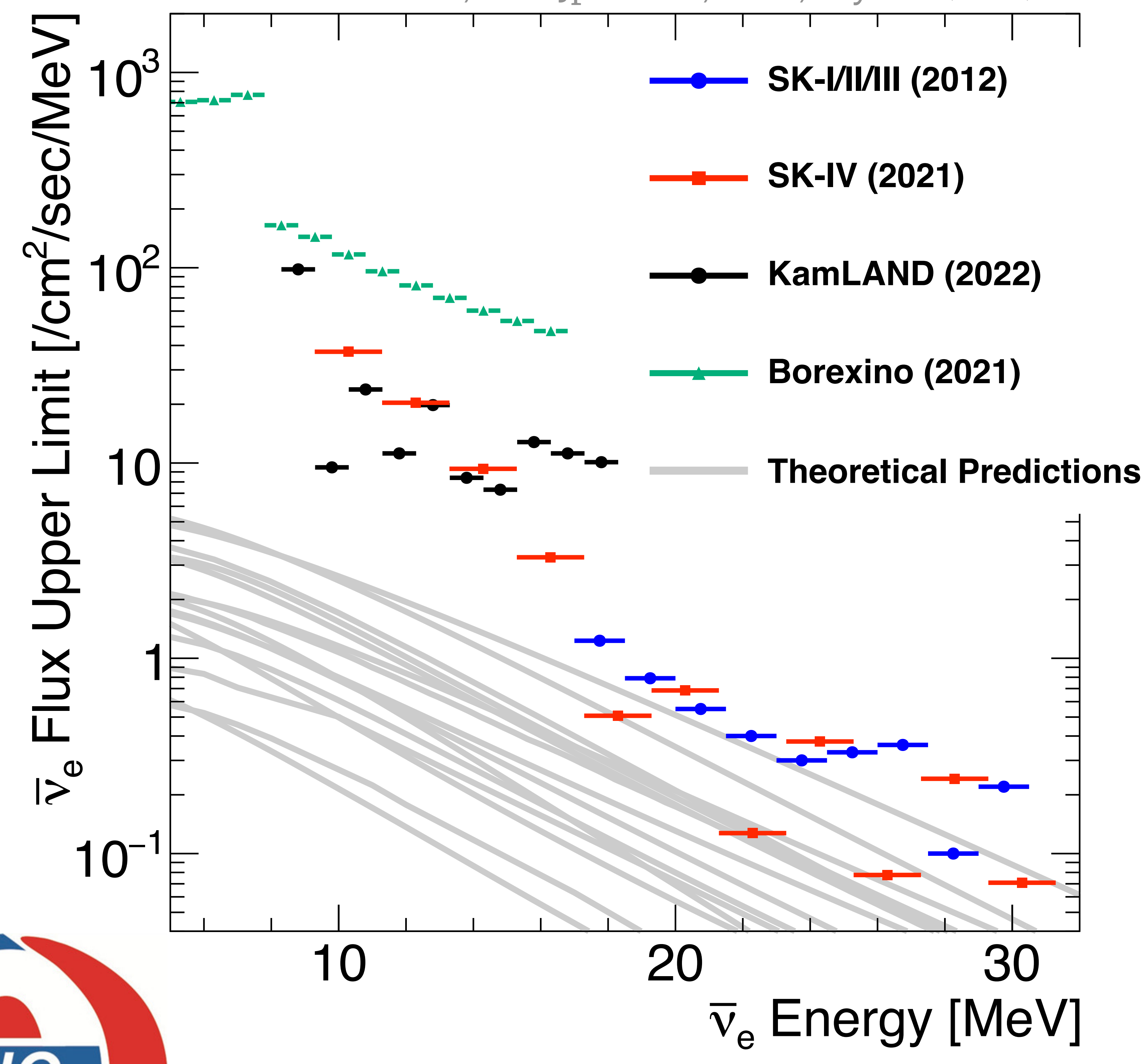
Highlight of recent search and prospects

<u>Status of DSNB search</u>

- Representative detectors
  - Liquid scintillator (LS): KamLAND(1 kt), Borexino (O(100) t)
  - Water-Cherenkov (WC): Super-Kamiokande(22.5 kt), SNO(0.7 kt)
    - Gd loaded WC detector: **SK-Gd**
      ➡ Latest result will be shown later

- Next-generation experiments for DSNB observations
  - WC: Hyper-Kamiokande
  - LS: JUNO

Based on S.Ando et al., Proc. Jpn. Acad., Ser. B, Phys. 99 (2023) 10



DSNB searches

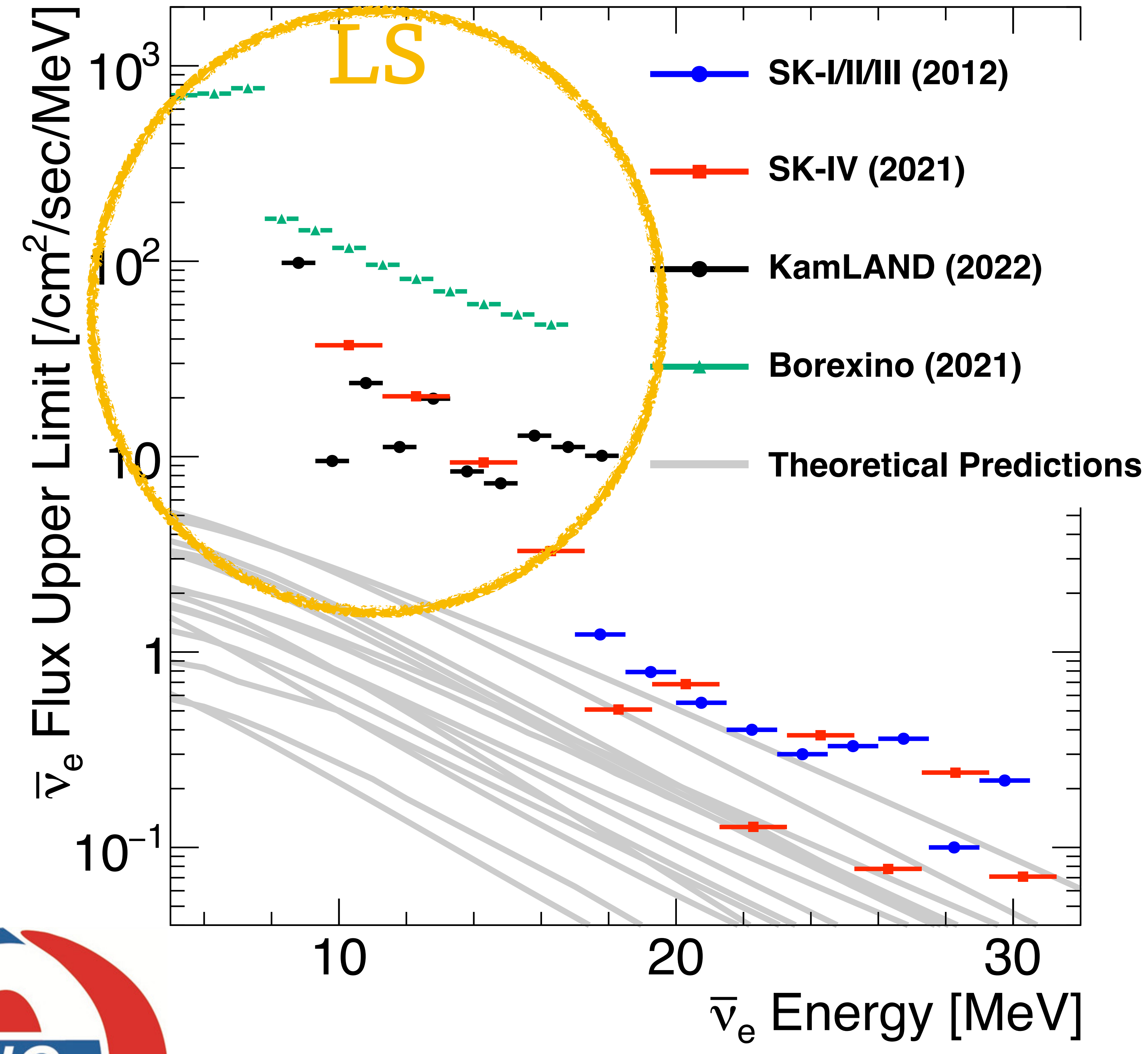
Highlight of recent search and prospects

Status of DSNB search

- Representative detectors
  - Liquid scintillator (LS): KamLAND(1 kt), Borexino (O(100) t)
  - Water-Cherenkov (WC): Super-Kamiokande(22.5 kt), SNO(0.7 kt)
    - Gd loaded WC detector: **SK-Gd**
      ➡ Latest result will be shown later

- Next-generation experiments for DSNB observations
  - WC: Hyper-Kamiokande
  - LS: JUNO

Based on S.Ando et al., Proc. Jpn. Acad., Ser. B, Phys. 99 (2023) 10



DSNB searches

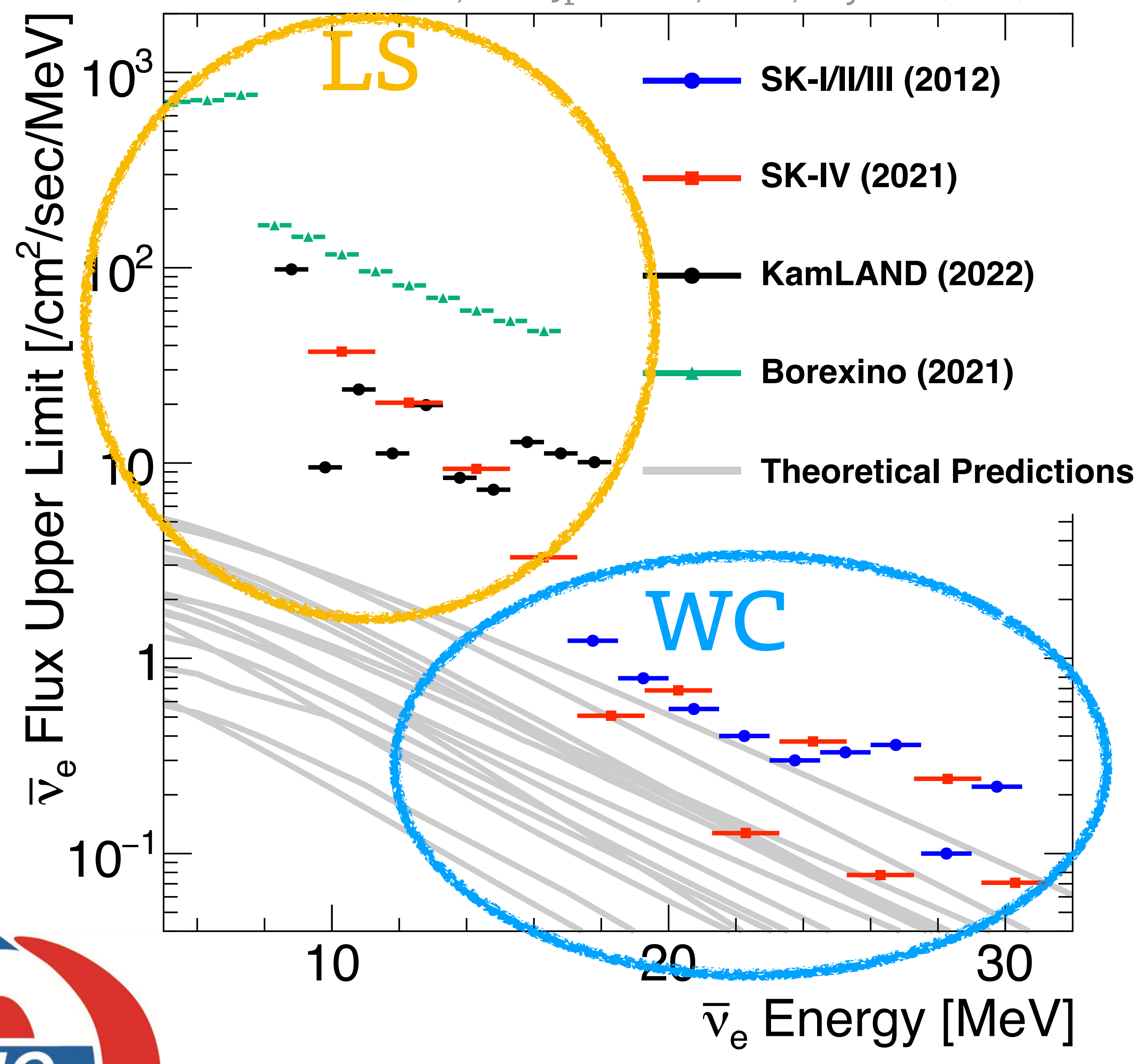
Highlight of recent search and prospects

Status of DSNB search

- Representative detectors
  - Liquid scintillator (LS): KamLAND(1 kt), Borexino (O(100) t)
  - Water-Cherenkov (WC): Super-Kamiokande(22.5 kt), SNO(0.7 kt)
    - Gd loaded WC detector: **SK-Gd**
      ➡ Latest result will be shown later

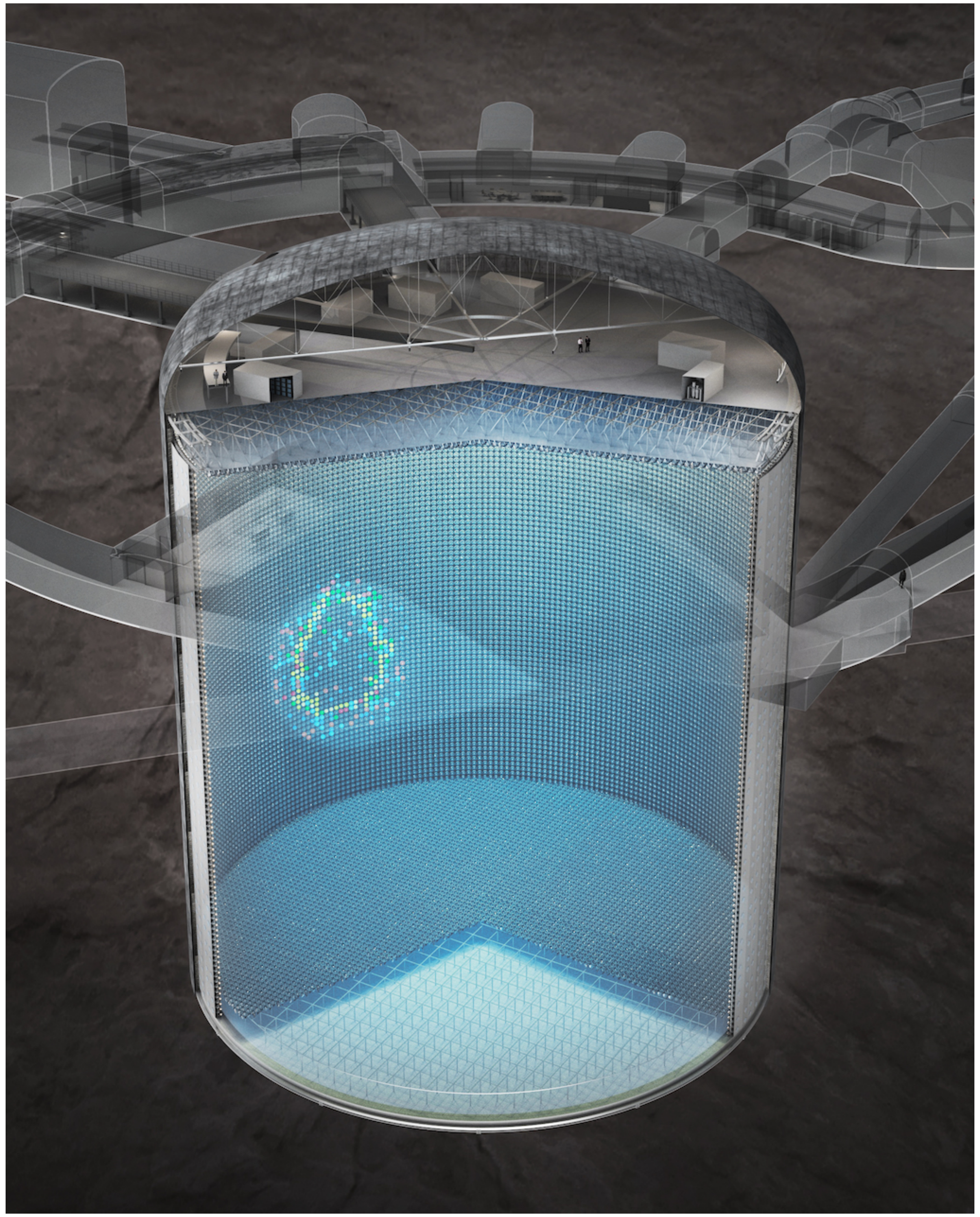
- Next-generation experiments for DSNB observations
  - WC: Hyper-Kamiokande
  - LS: JUNO

Based on S.Ando et al., Proc. Jpn. Acad., Ser. B, Phys. 99 (2023) 10



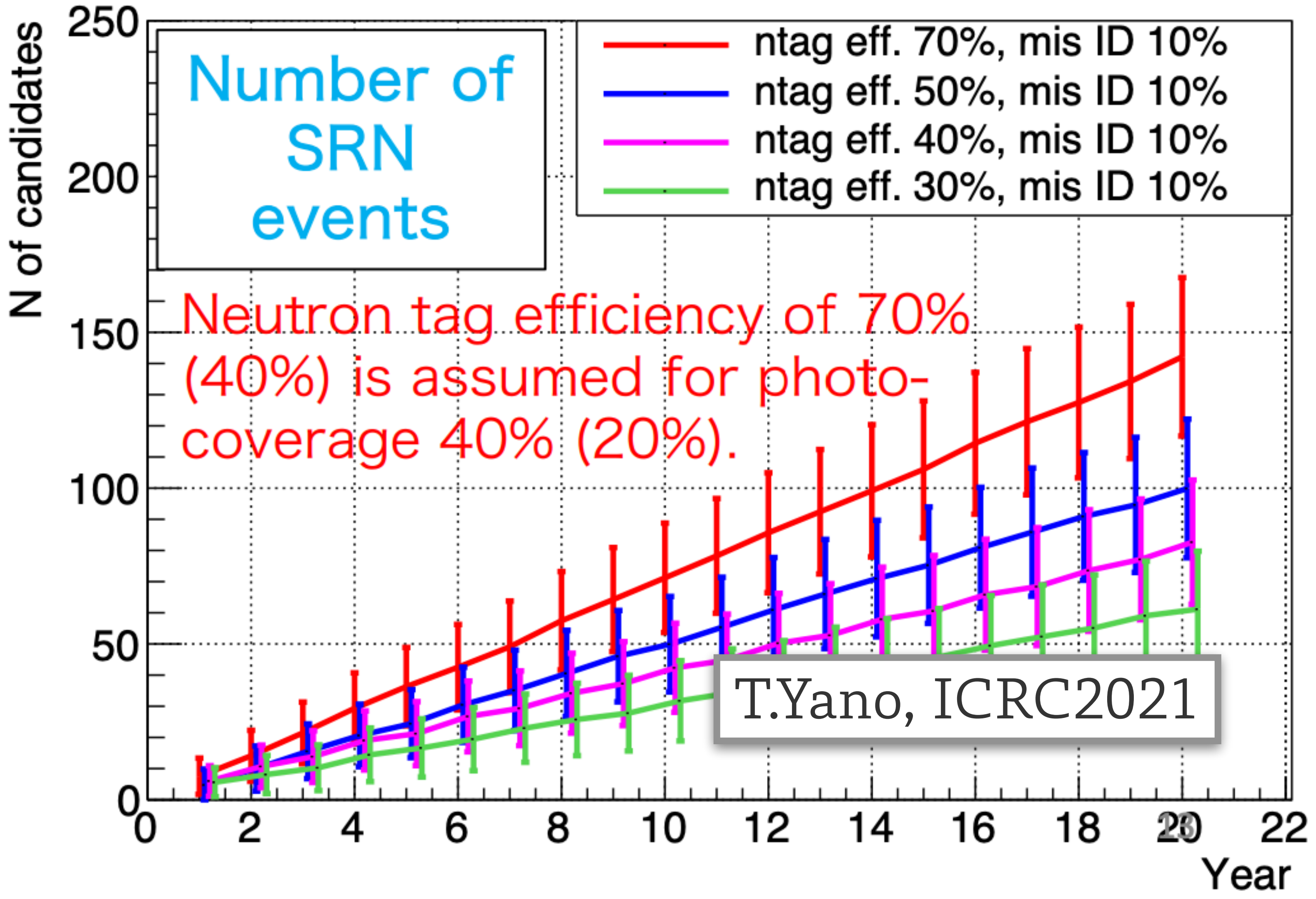
Future experiments

Larger DSNB detectors



Hyper-Kamiokande (Moriyama, Plenary 646) (Beauchene, Poster 218)

- 258 kton WC detector@Kamioka, Japan
- Start from 2027
- expected to >4 σ in 10 yr due to its largest volume and upgraded photosensor

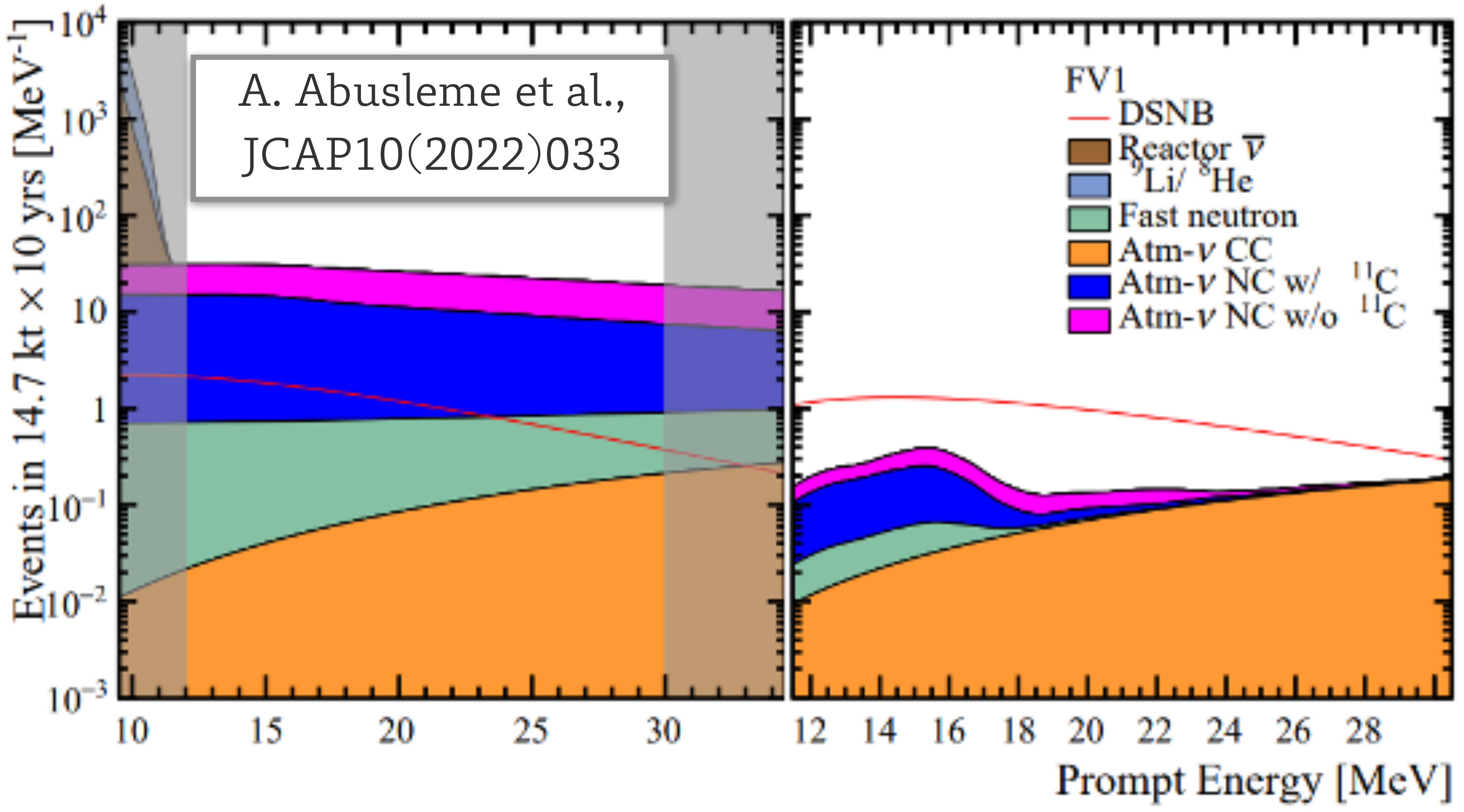


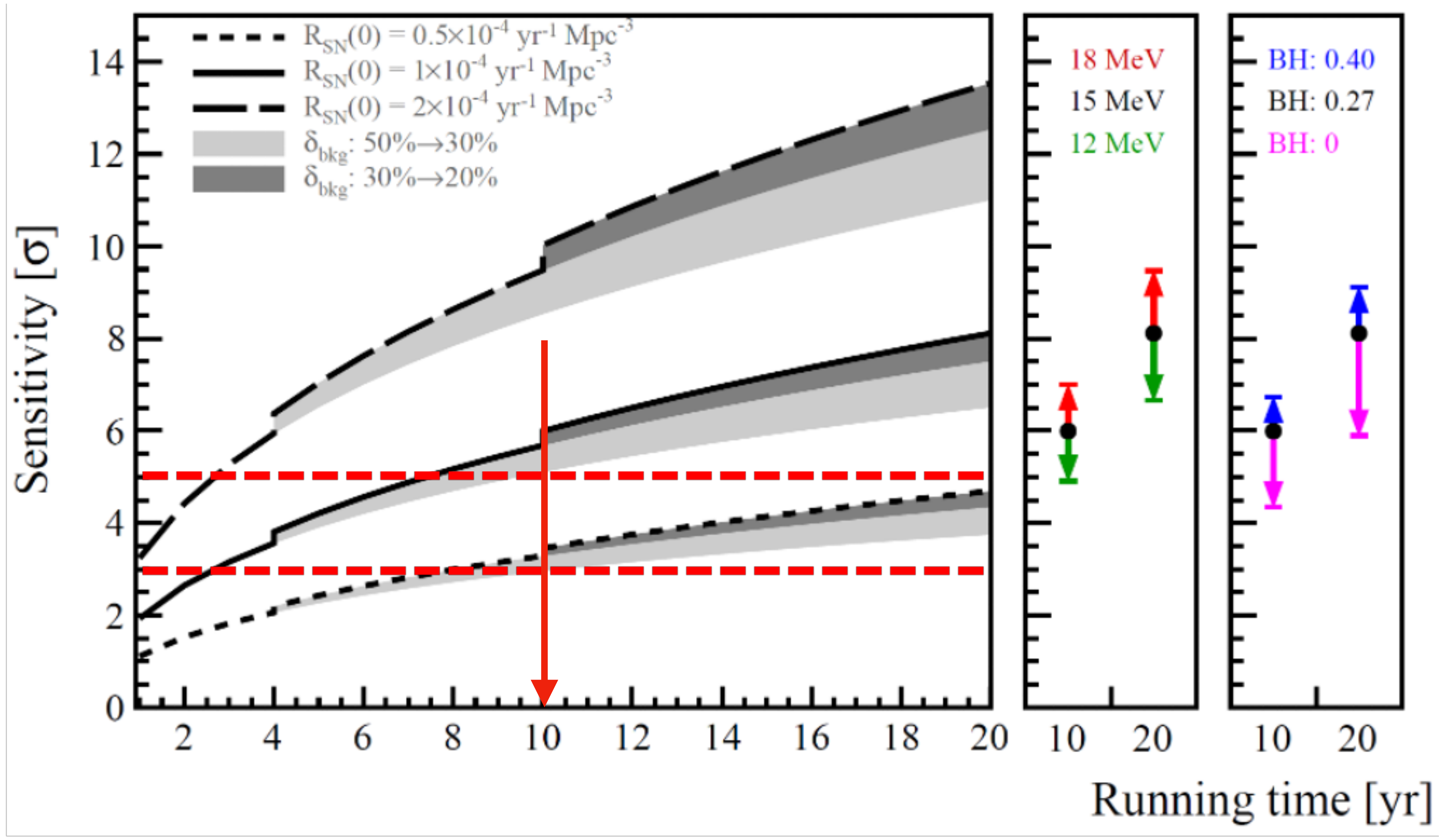
Future experiments

Larger DSNB detectors

JUNO (Huang, Poster 477) (Jun, plenary 709)

- 20 kton LS detector@Jianmen, China ➡ Finish construction in 2024
- 80% of signal efficiency and effective background reduction using muon veto and PSD method
  ➡ S/B ~ 3.5
- 5 σ with 10 yr for optimistic prediction



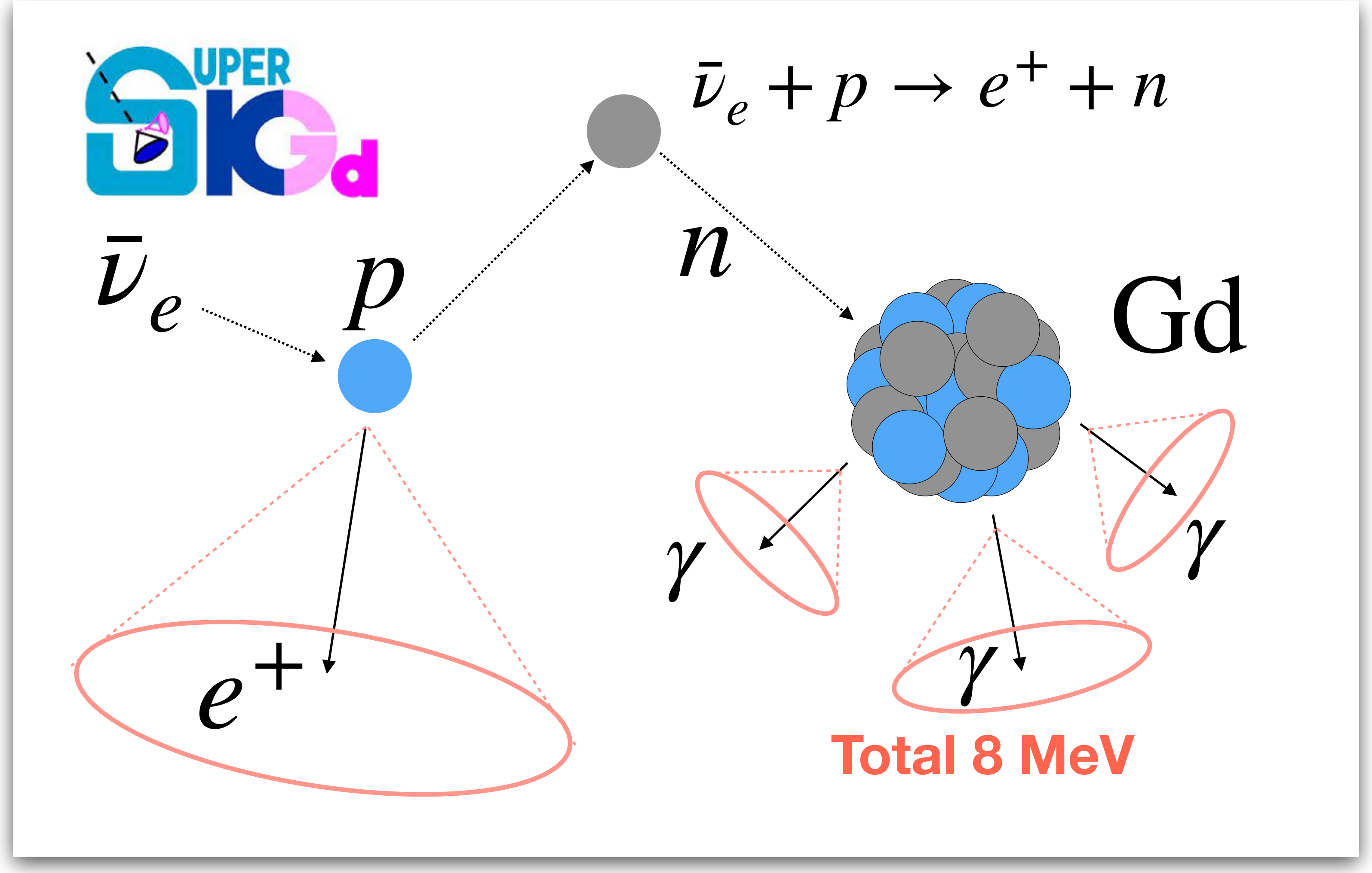


Latest Super-Kamiokande result with Gd

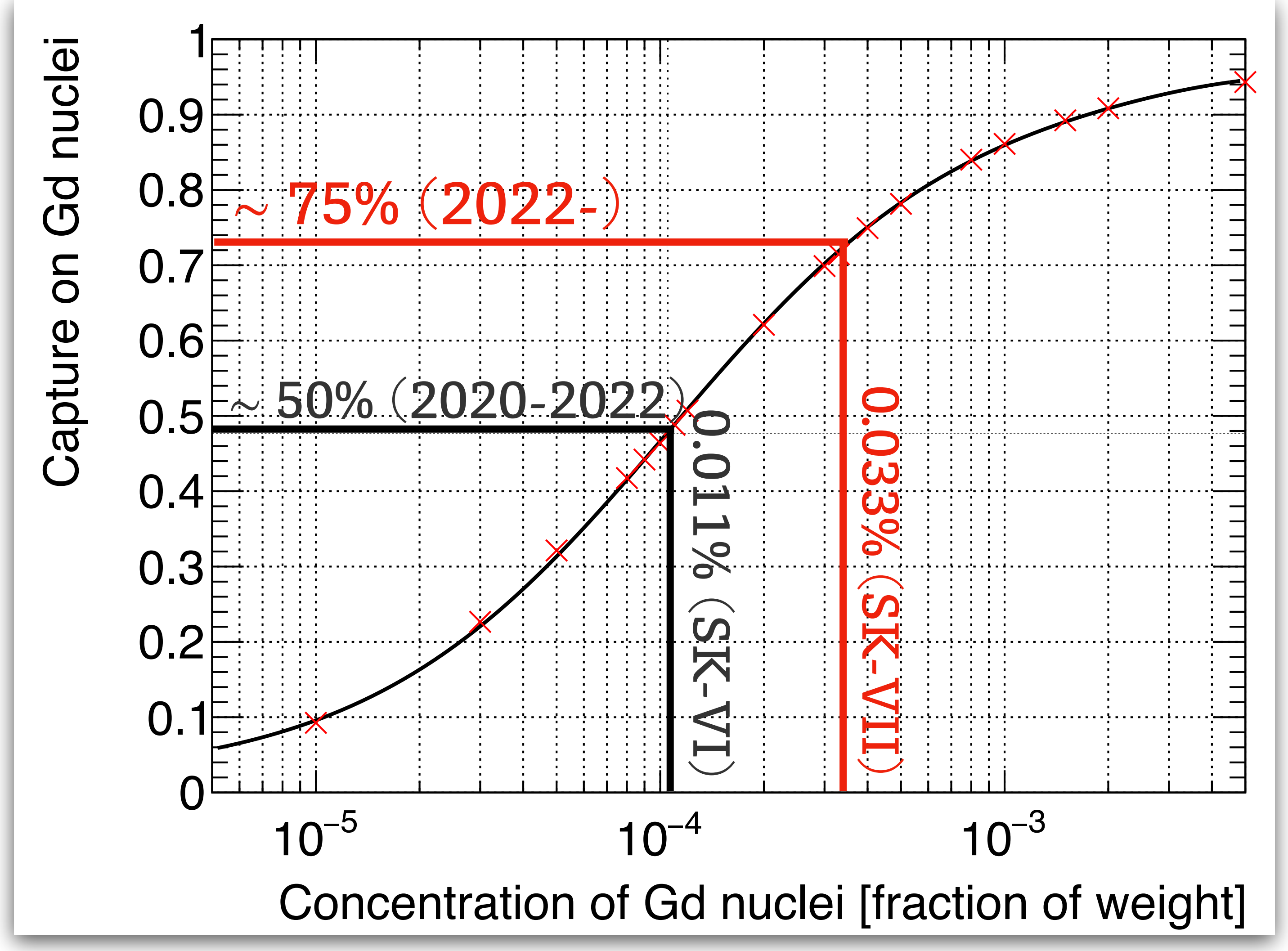
Super-Kamiokande

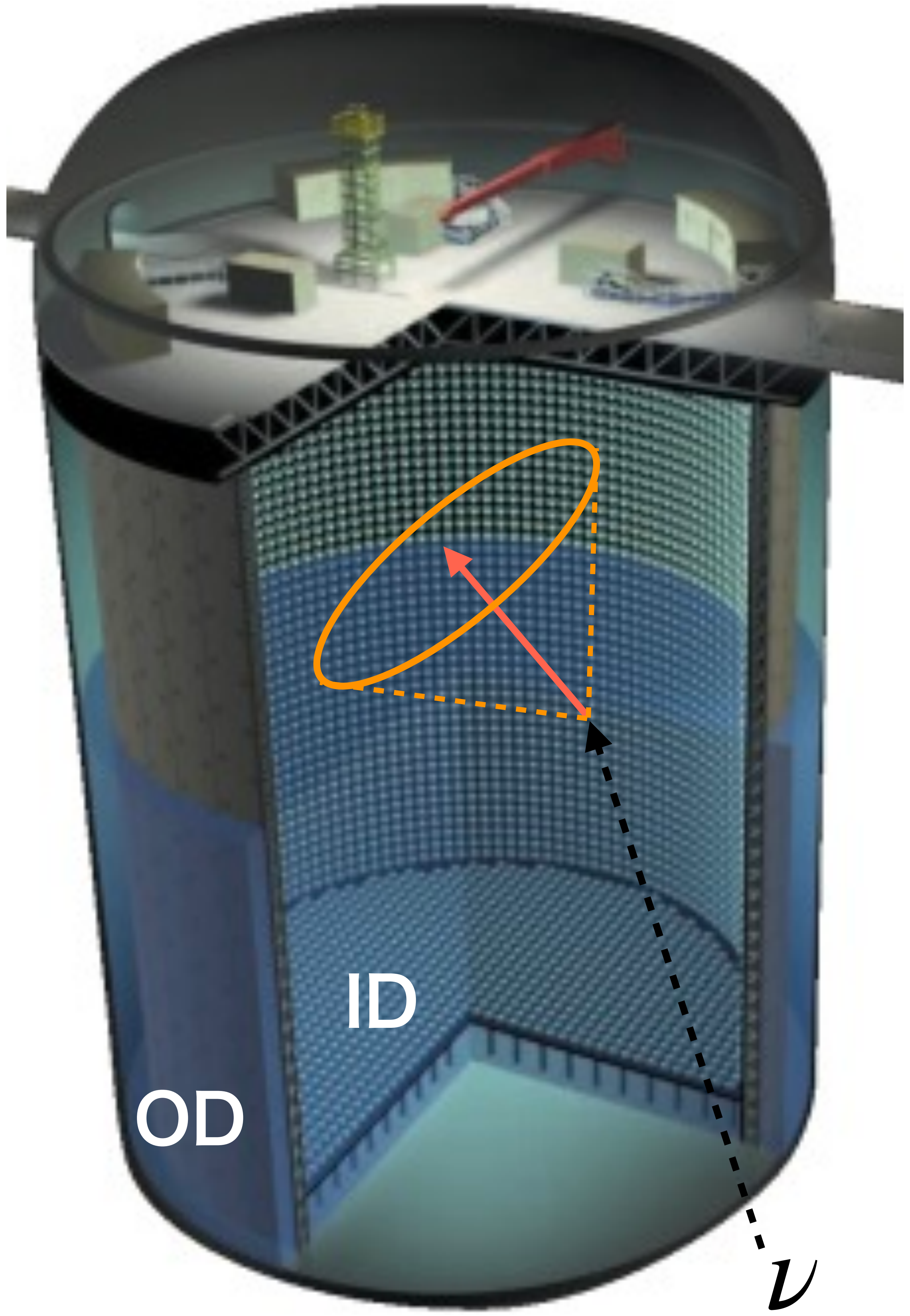
The world largest underground water Cherenkov detector

- Super-Kamiokande (SK): WC detector
  - Location: 1000 m underground@Kamioka mine, Japan
- Phase: exposure with 22.5 kton times…
  - No neutron tagging (1996 - 2008): 3033 d (SK-I — III)
  - pure-water with neutron tagging (2008 - 2018): 2970 d (SK-IV)
  - **Gd-loaded water with neutron tagging (2020-present): >956 d (SK-VI, VII)**



Beacom and Vagins (2004)

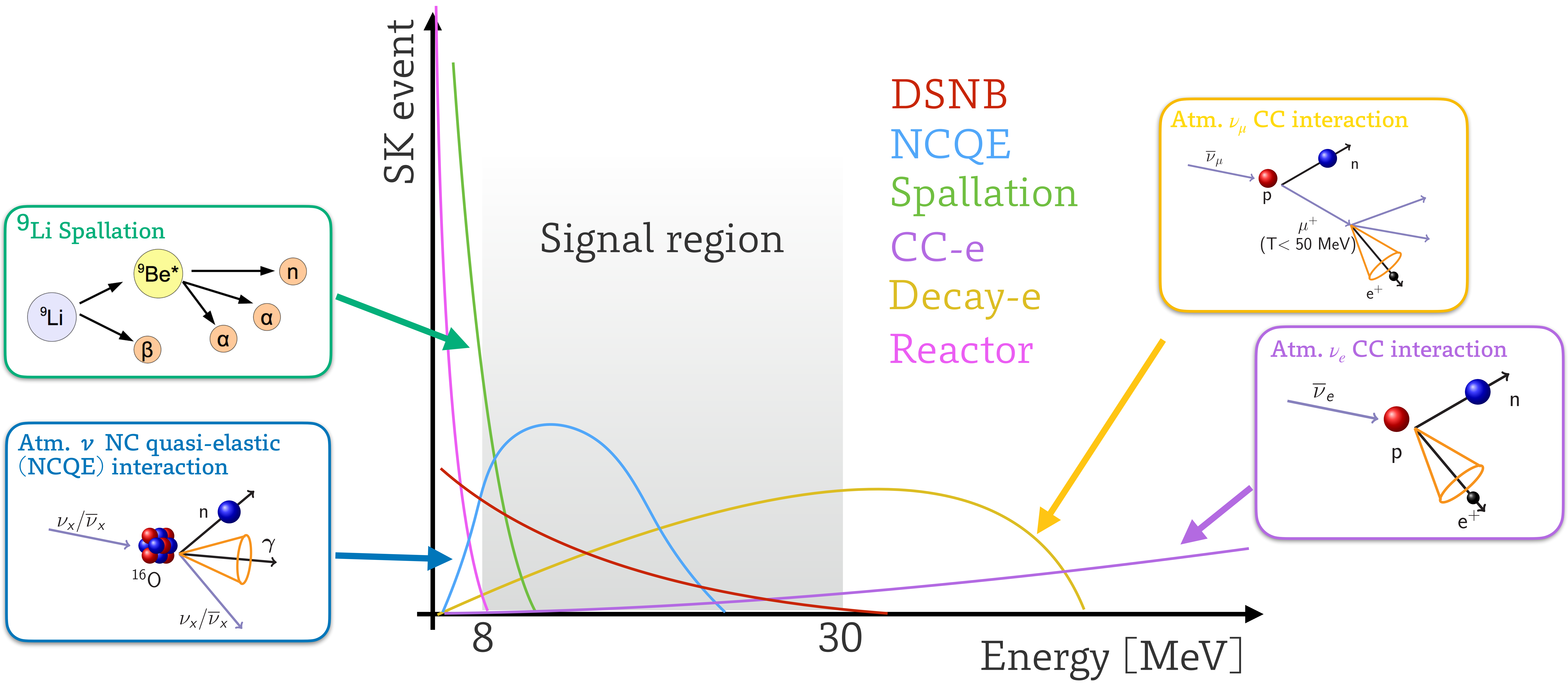




http://www-sk.icrr.u-tokyo.ac.jp/sk/detector/introduction.html

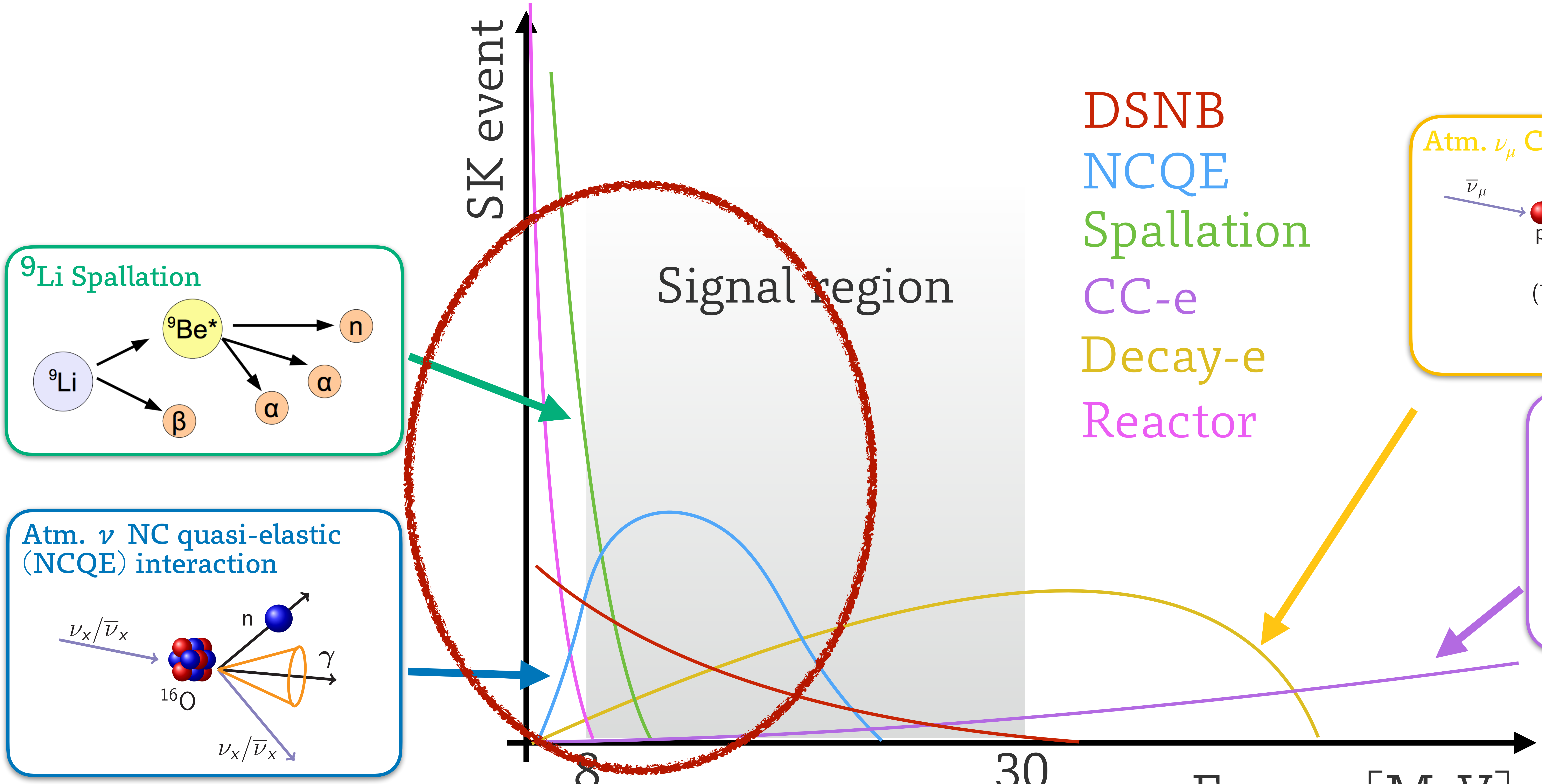
DSNB search in SK-Gd

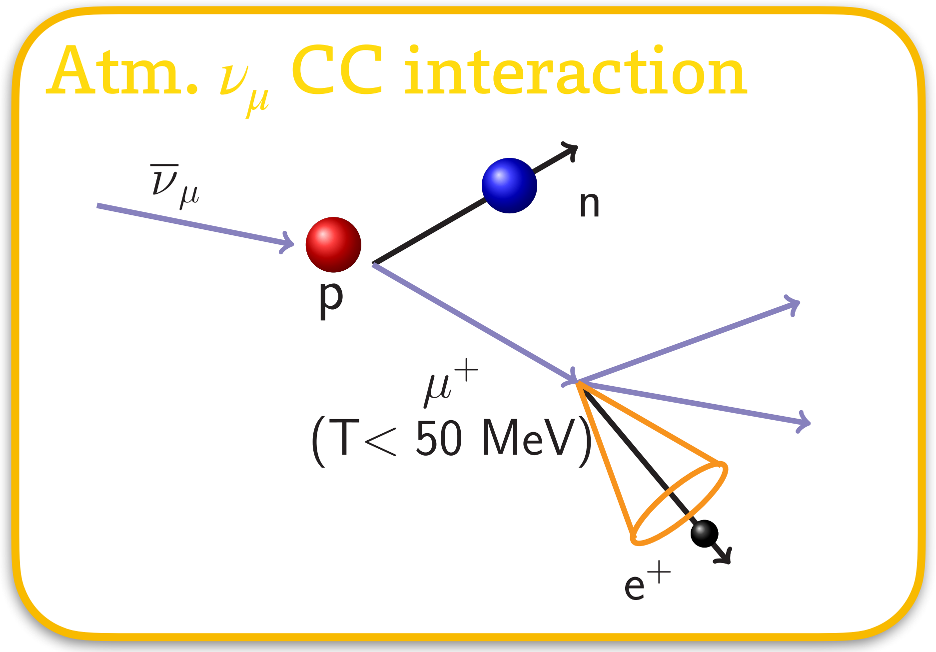
Signal and background

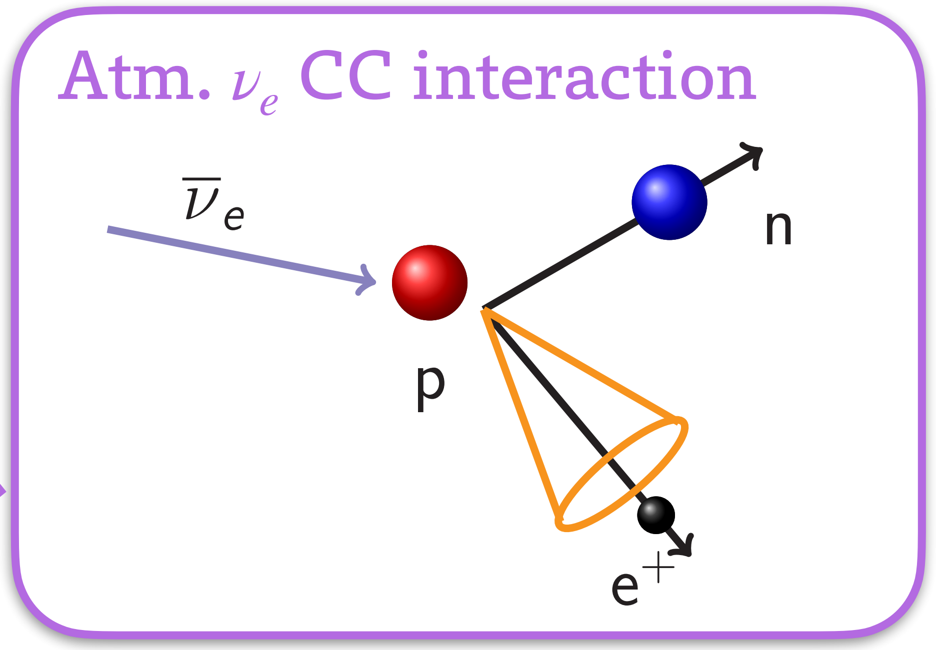


DSNB search in SK-Gd

Signal and background



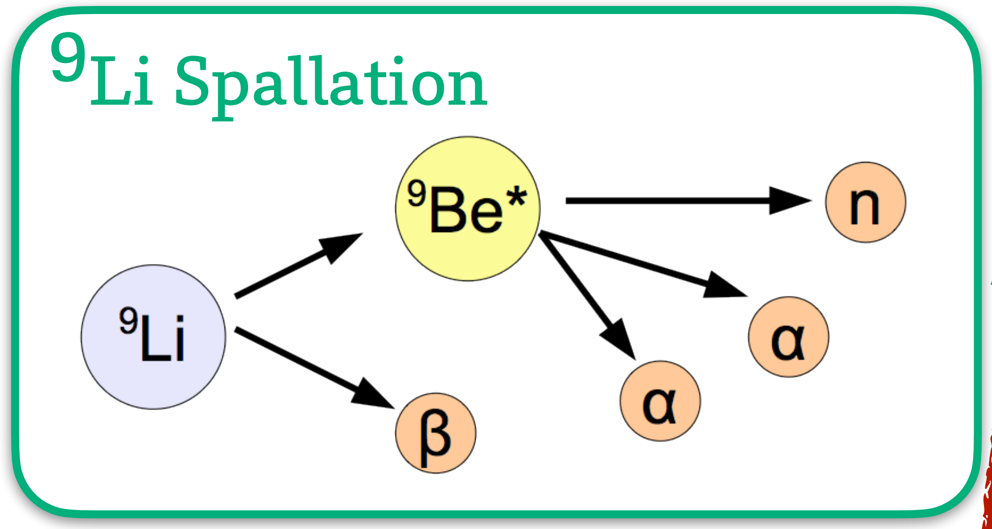


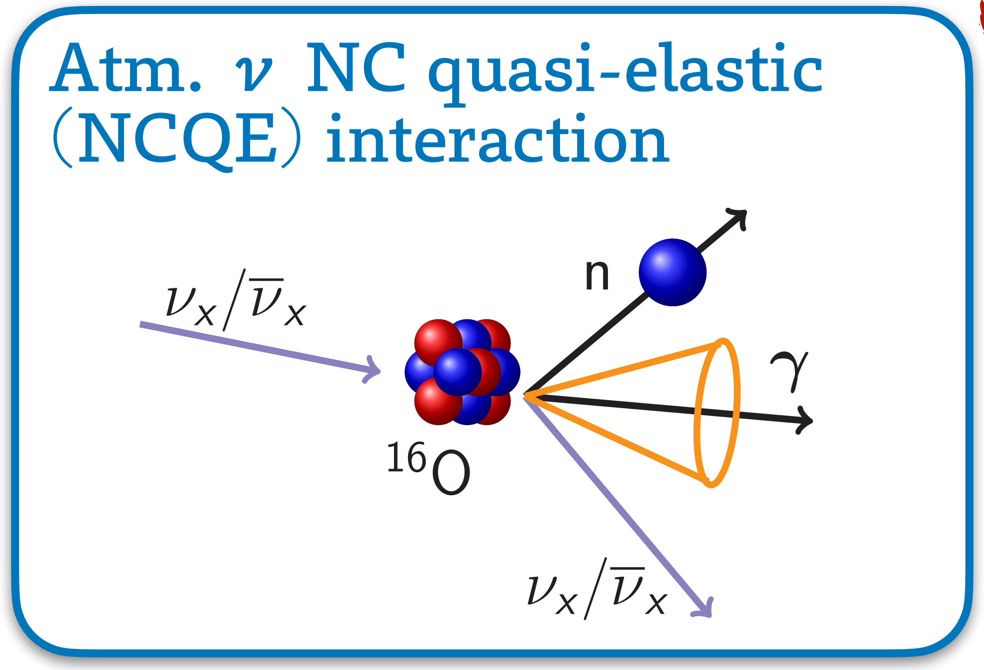


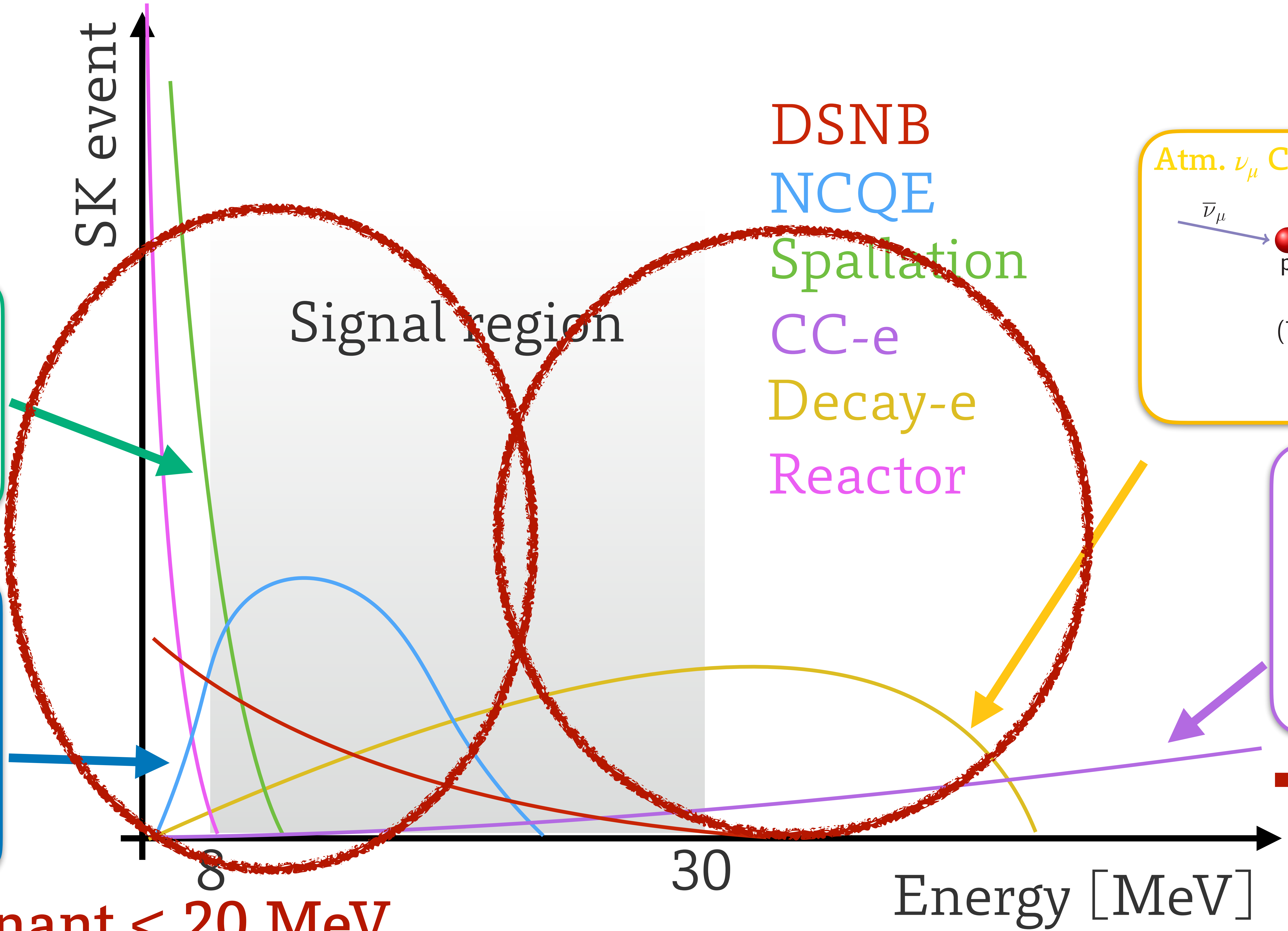
➡ Dominant < 20 MeV

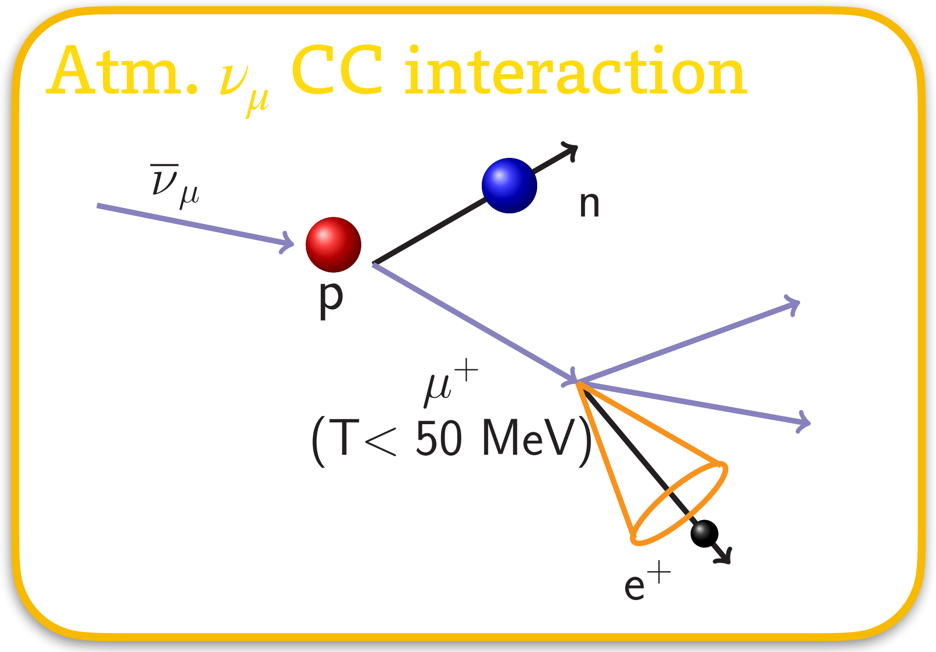
DSNB search in SK-Gd

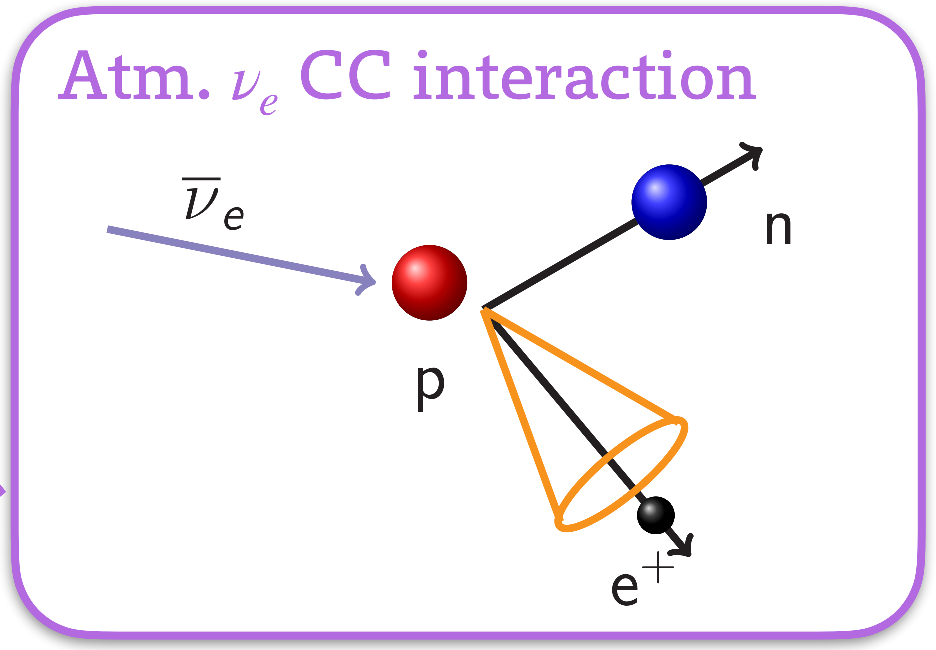
Signal and background











➡ Constraint using >30 MeV side-band

➡ Dominant < 20 MeV

SK-Gd first result of DSNB search

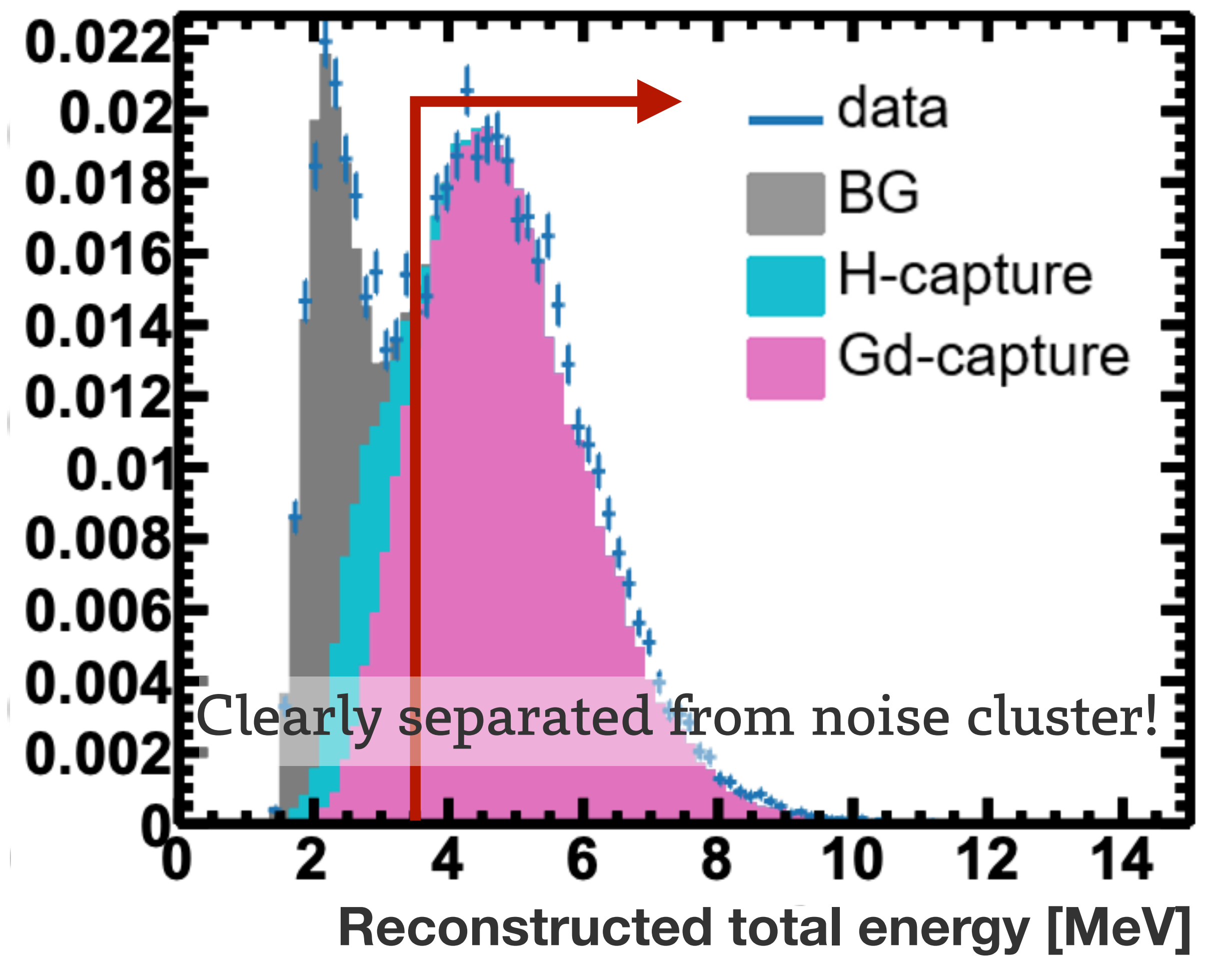
Quick analysis for proving power of neutron tagging with Gd

Highlight:

- 552.2 days with 0.01% Gd concentration (SK-VI)
- Cut based simple neutron reduction thanks to Gd
  ➡ **36% of n-tag. efficiency** (10-30% for pure-water SK with ML)
- N_n=1 event are selected as IBD candidate
  - Dominant background in signal peak: **NCQE**
- **Close to 2970 days of pure-water SK (SK-IV) limit**

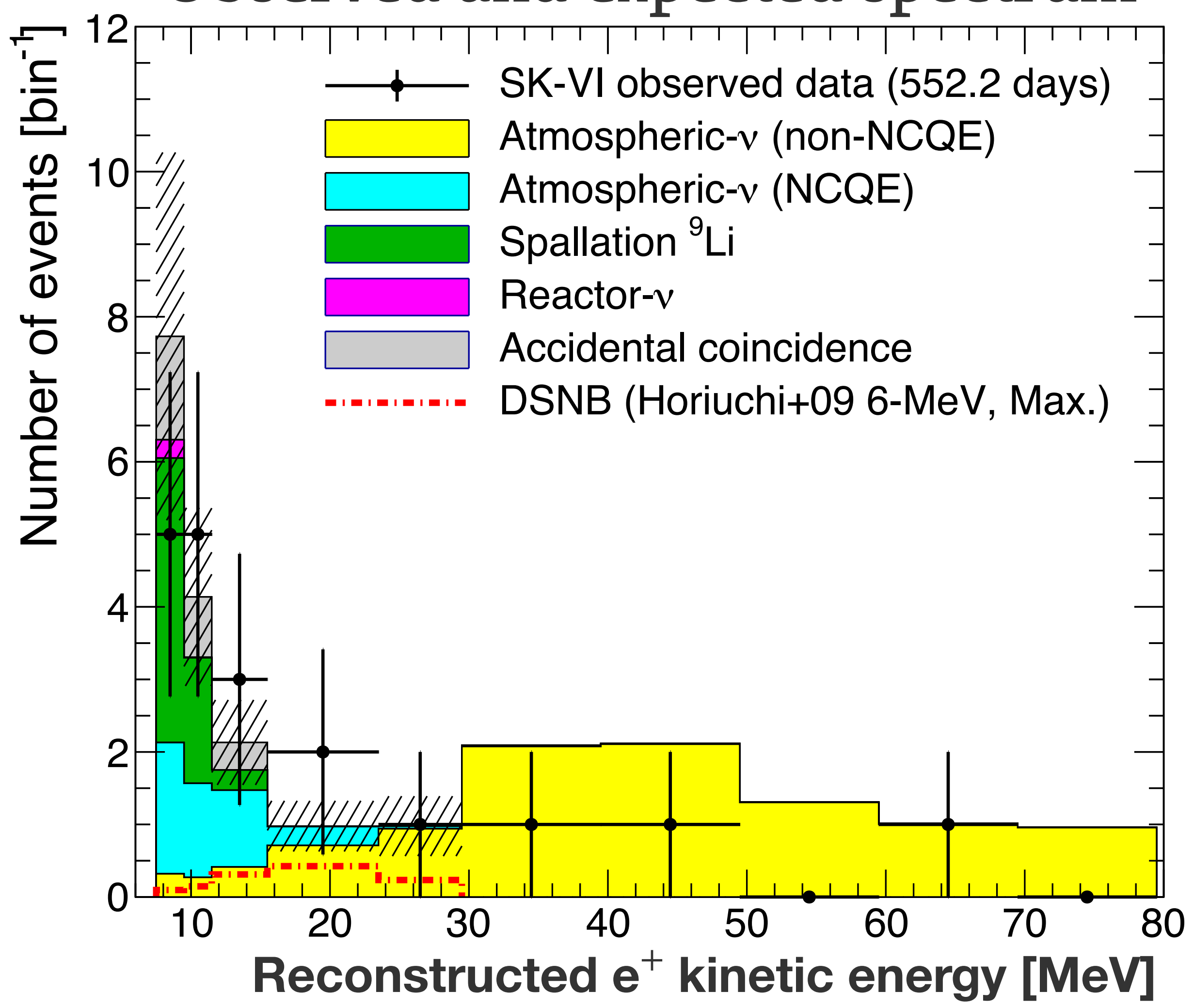
M. Harada et al.
(Super-Kamiokande Collaboration)
AstroPhys. J. L 951 L27 (2023)

Energy distribution for delayed signal



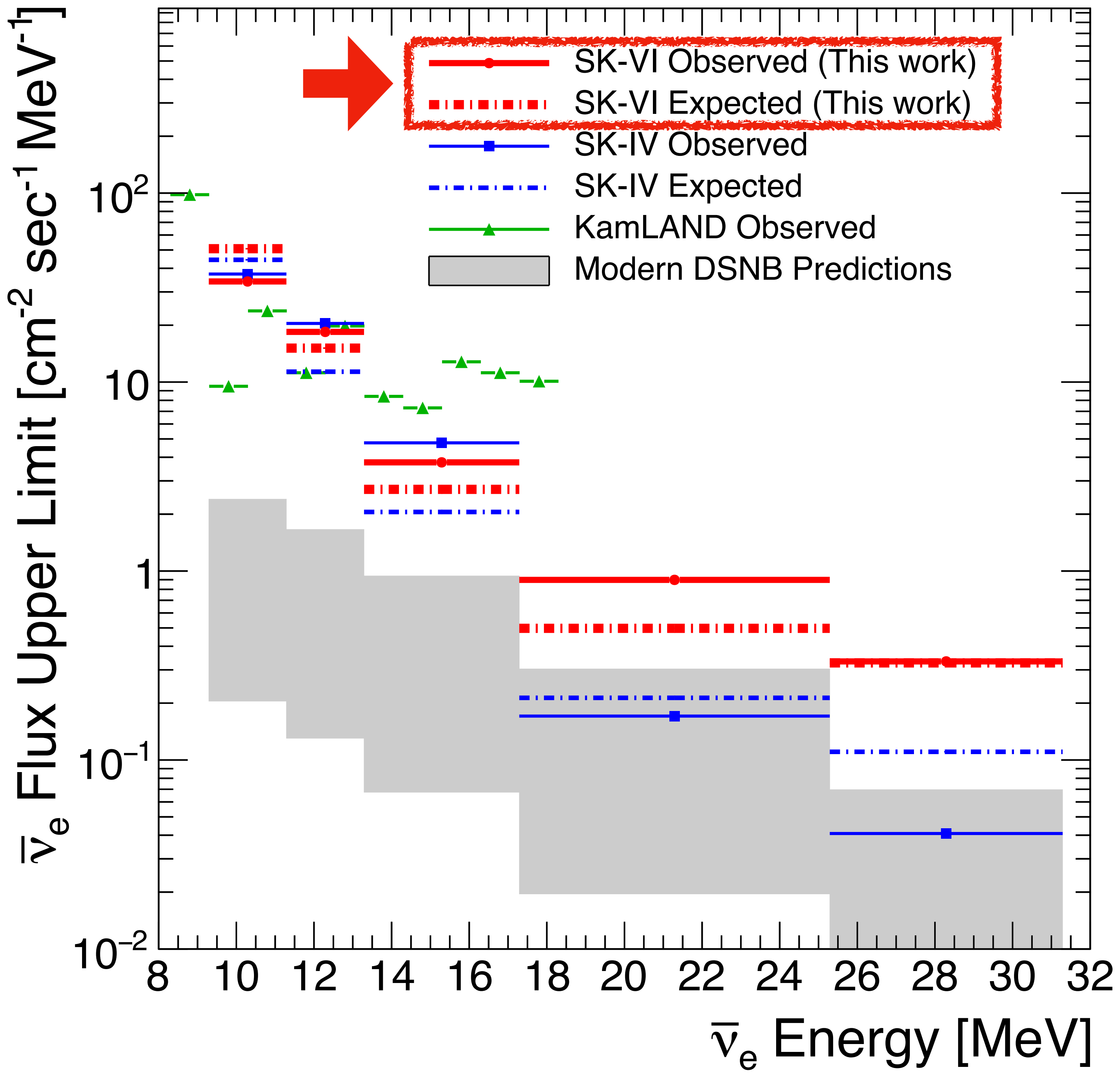
N_n=1

Observed and expected spectrum



No excess...

Differential flux upper limit



Latest analysis of SK-Gd

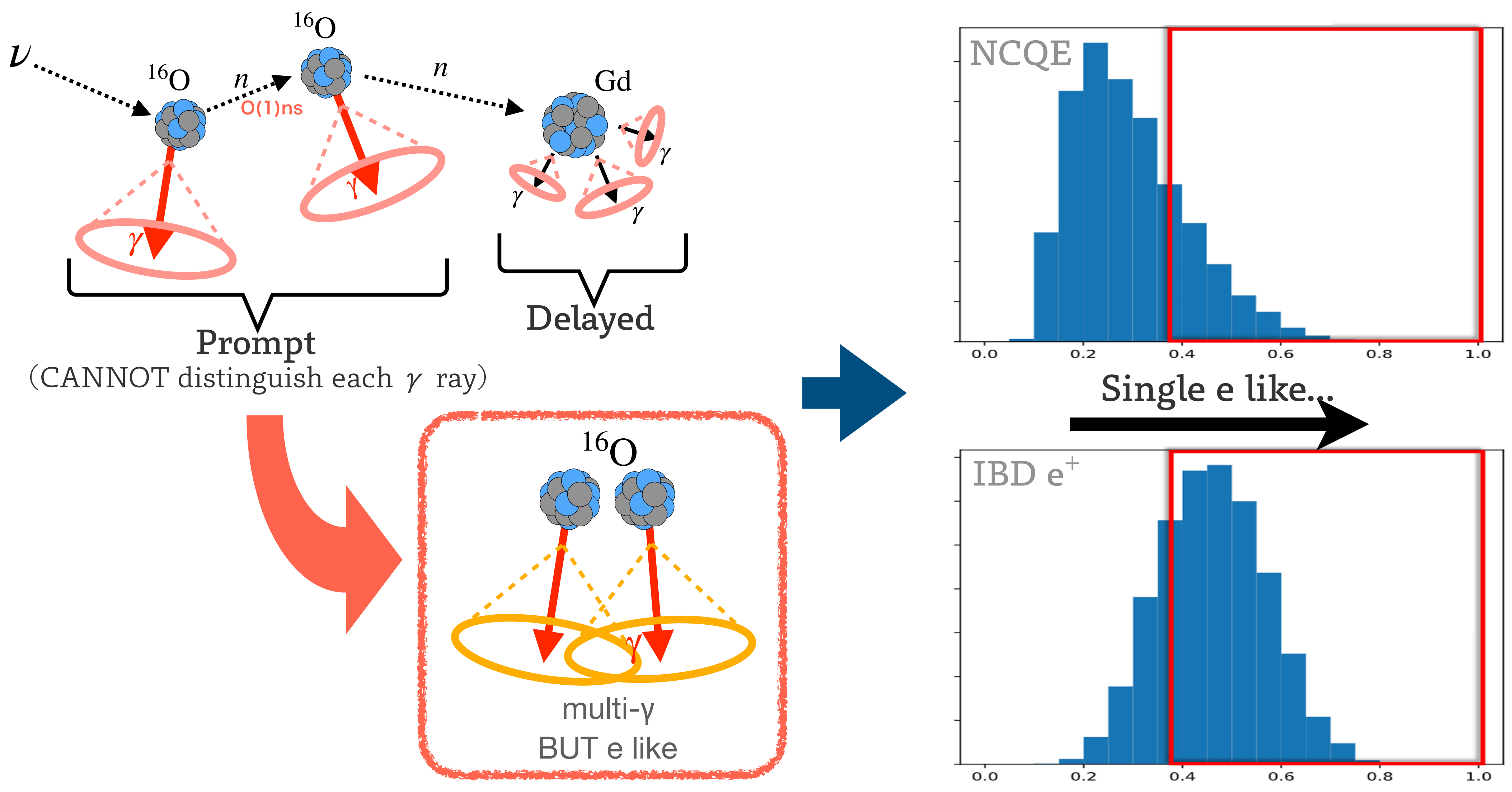
Analysis improvement

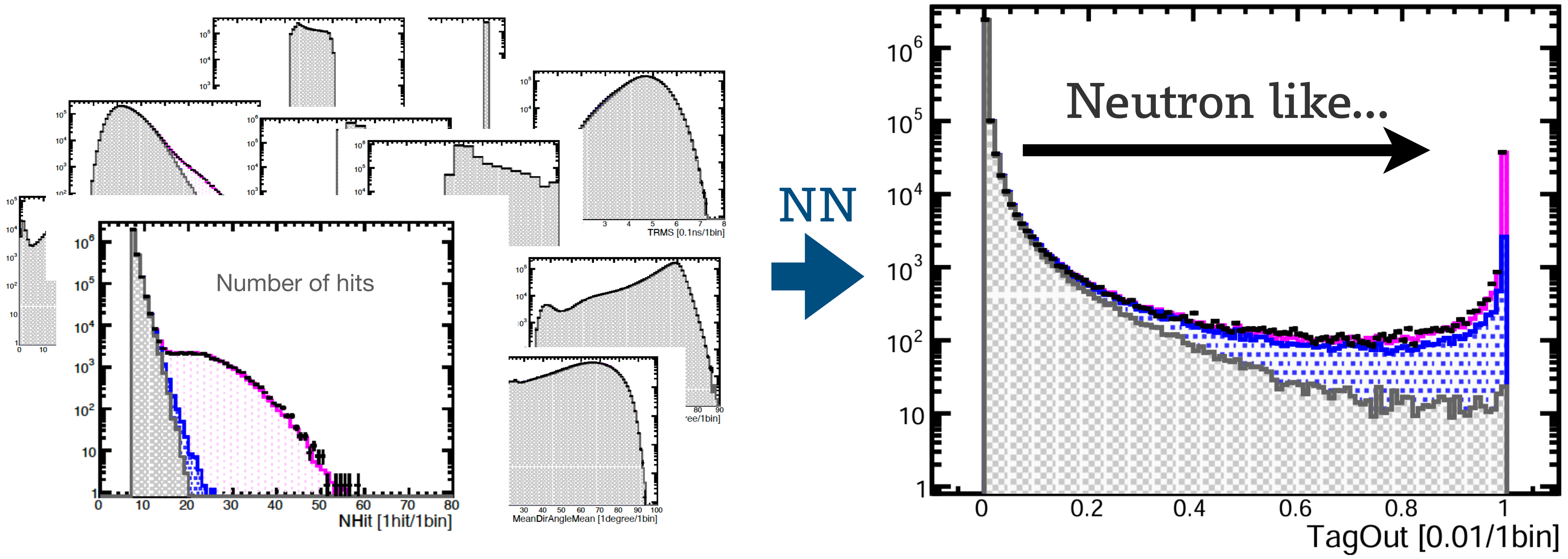
- SK-Gd continued observation and acquired additional 404 days with 0.03w% Gd (SK-VII)
  ➡ <u>Totally 956 days of SK-Gd data</u>

<u>**Analysis Improvement**</u> (Santos et al., poster 637)

- Developed new reduction for NCQE event using gamma-ray cut variable
  ➡ Further reduced **~90% of NCQE**

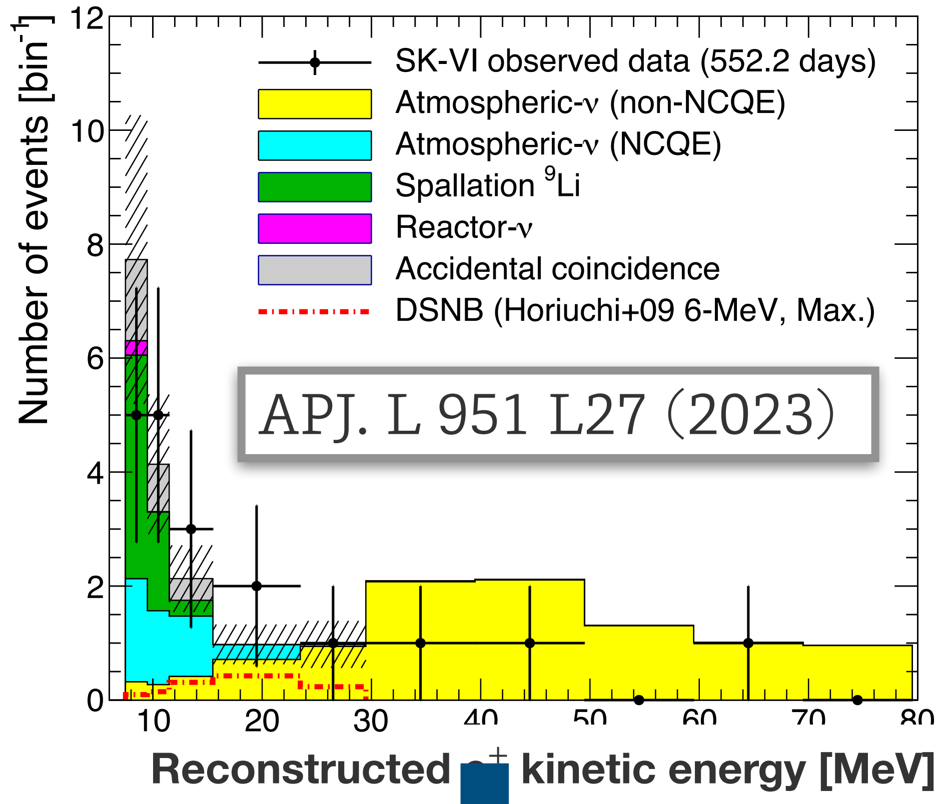
- Developed new neutron tagging methods based on multivriate analysis,
  - Search neutrons with 500 μs window
    ➡ achieving **>60% efficiency** in SK-VII



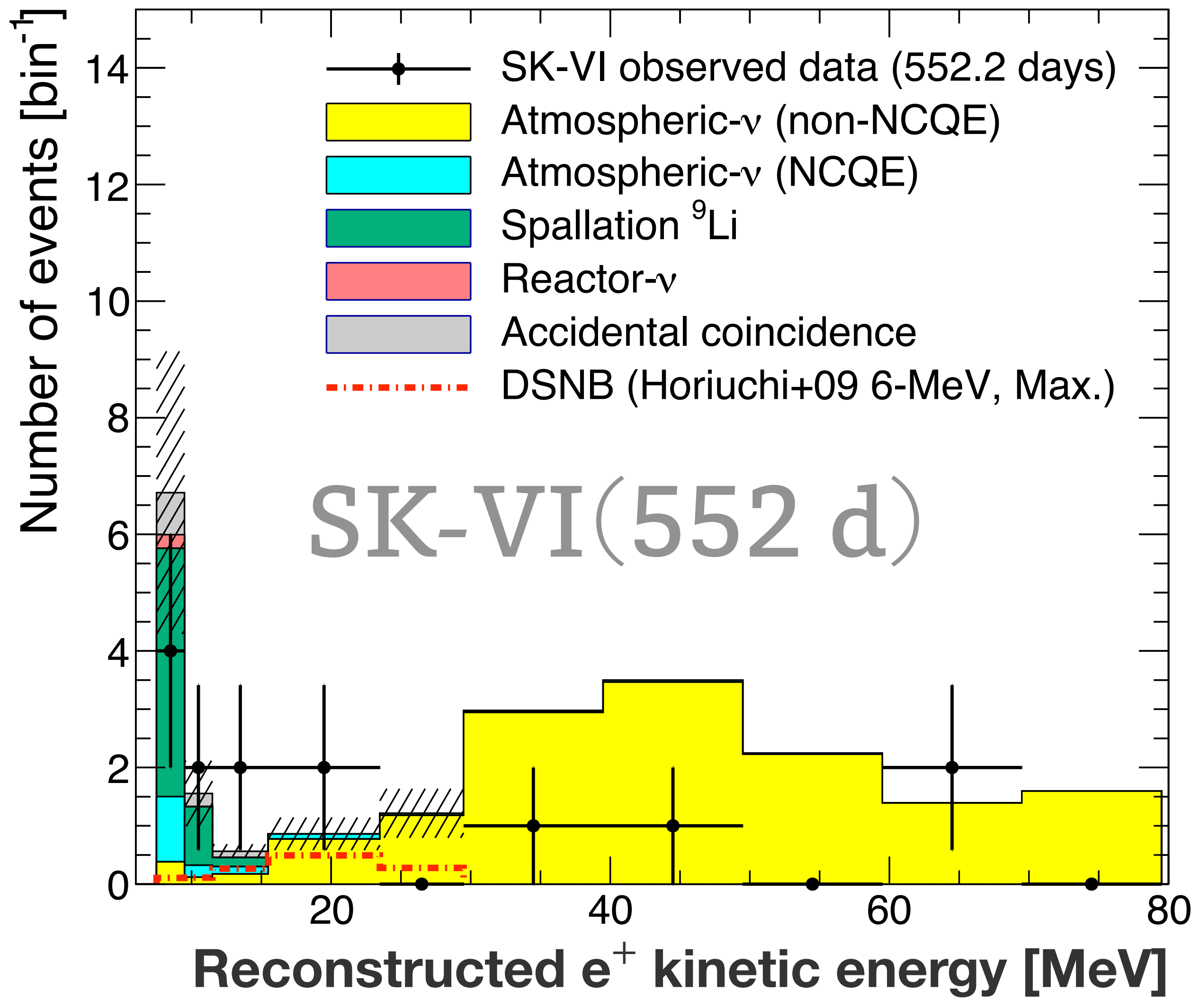


Results

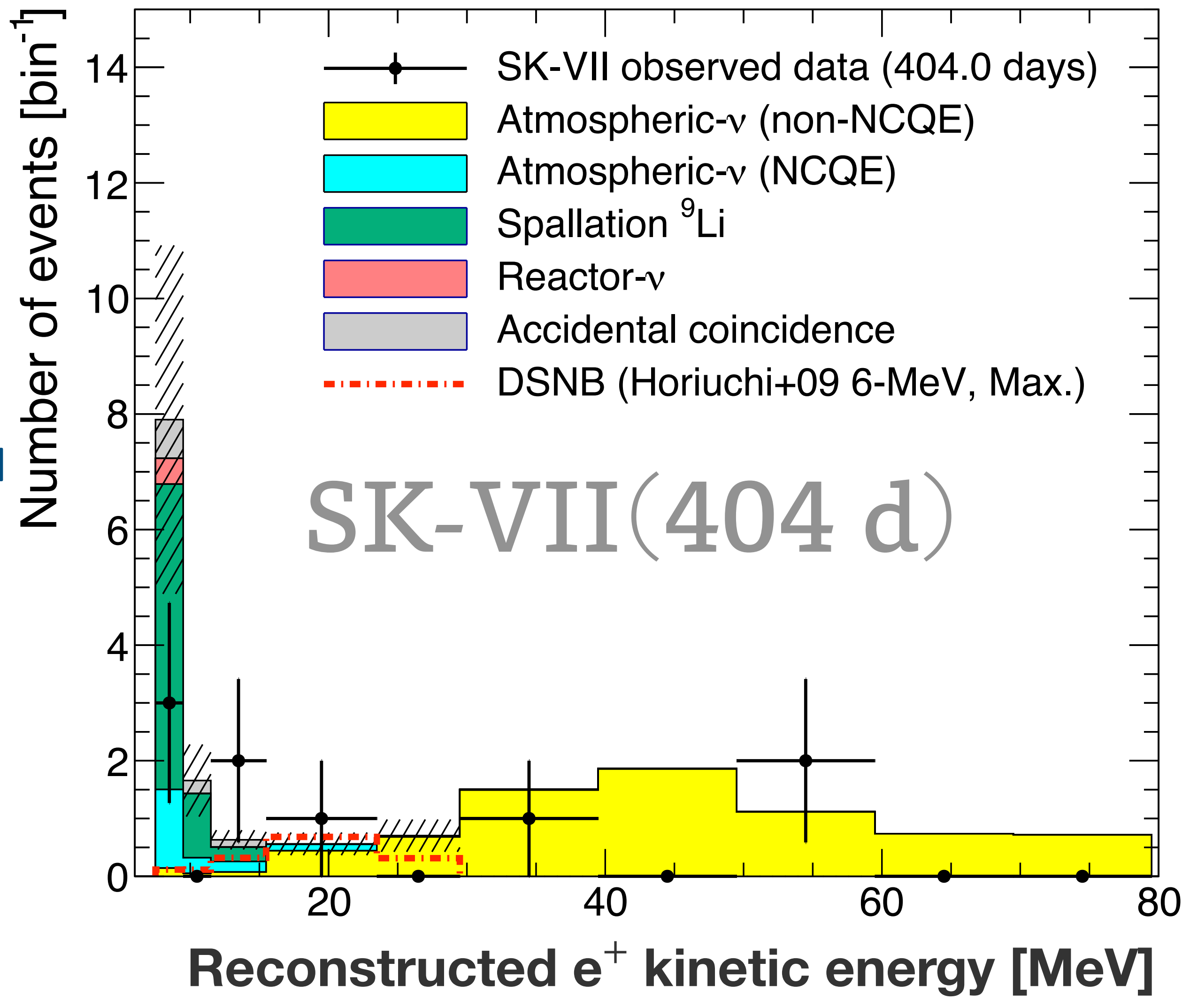
SK-Gd energy spectrum



New n-tag, NCQE reduction



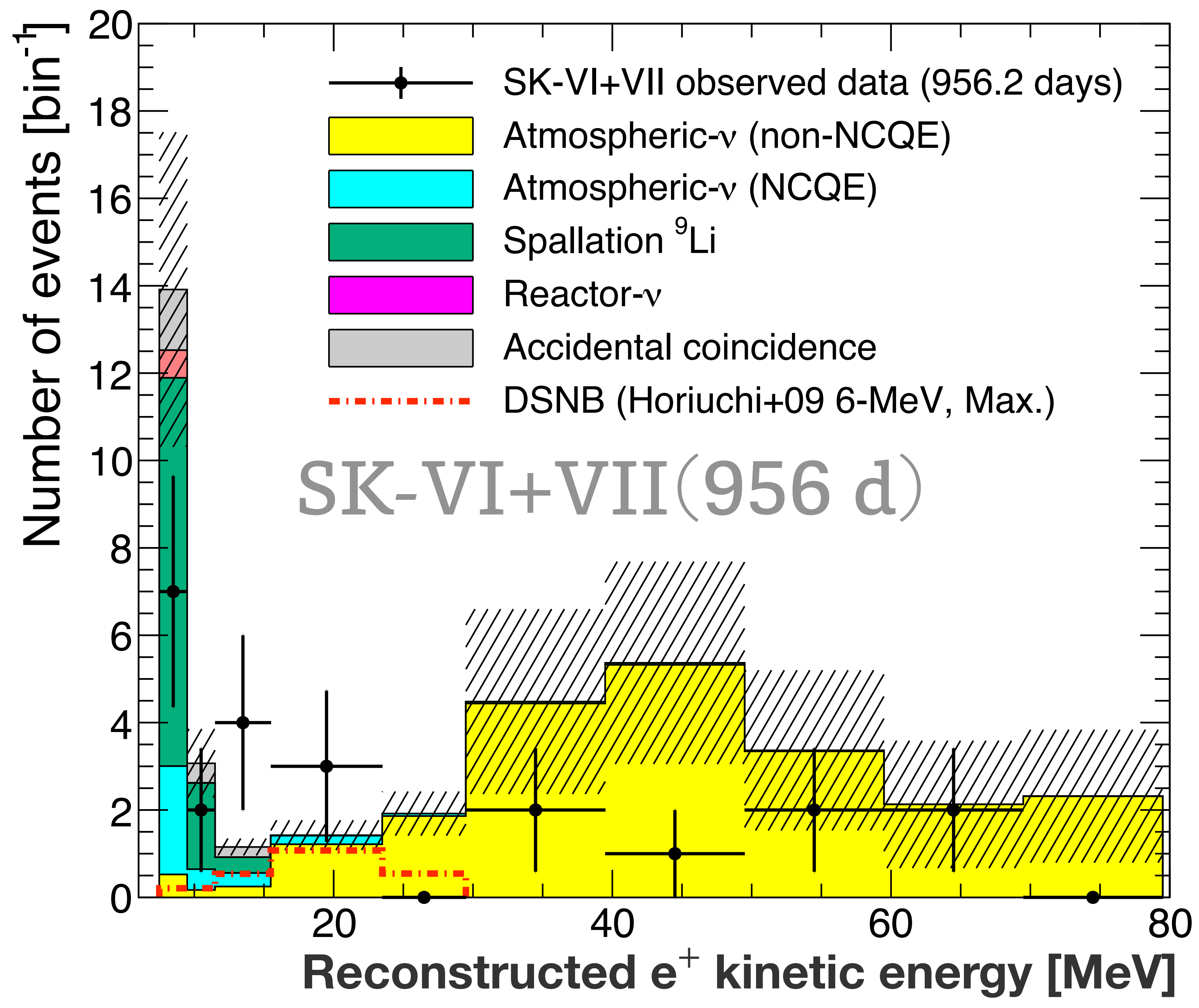
+



=

Highlight:

- Additional 404 days with 0.03% Gd ➡ Totally 956 days SK-Gd data
  - Select only $N_n = 1$
  - New neutron ID and background reduction
- No signal obvious excess, but indicates (min. p-value=0.04)

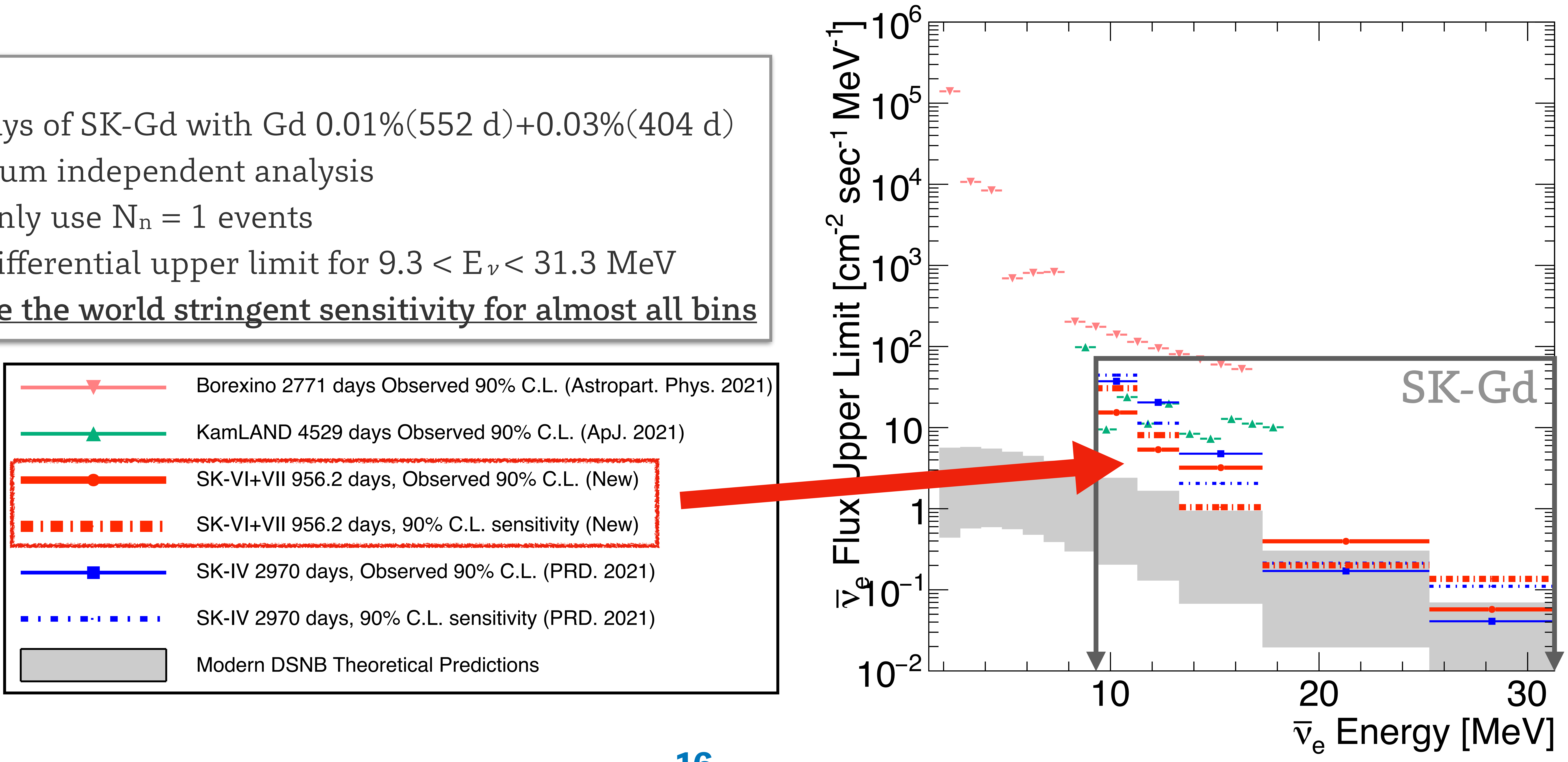


Differential flux upper limits

Spectral-independent analysis

Highlight:

- 956 days of SK-Gd with Gd 0.01%(552 d)+0.03%(404 d)
  Spectrum independent analysis
    - Only use $N_n = 1$ events
    - Differential upper limit for $9.3 < E_\nu < 31.3$ MeV
- Update the world stringent sensitivity for almost all bins

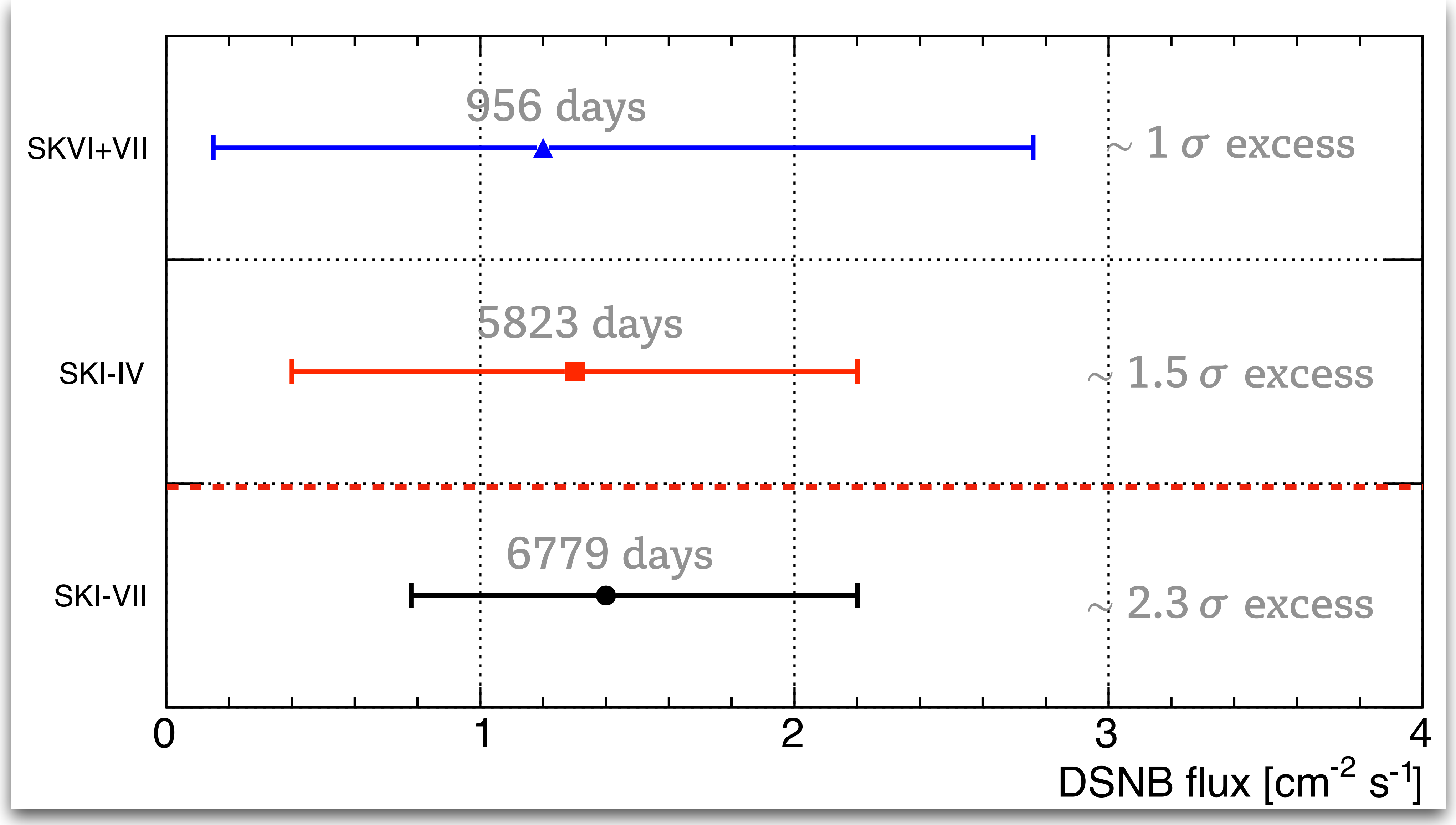


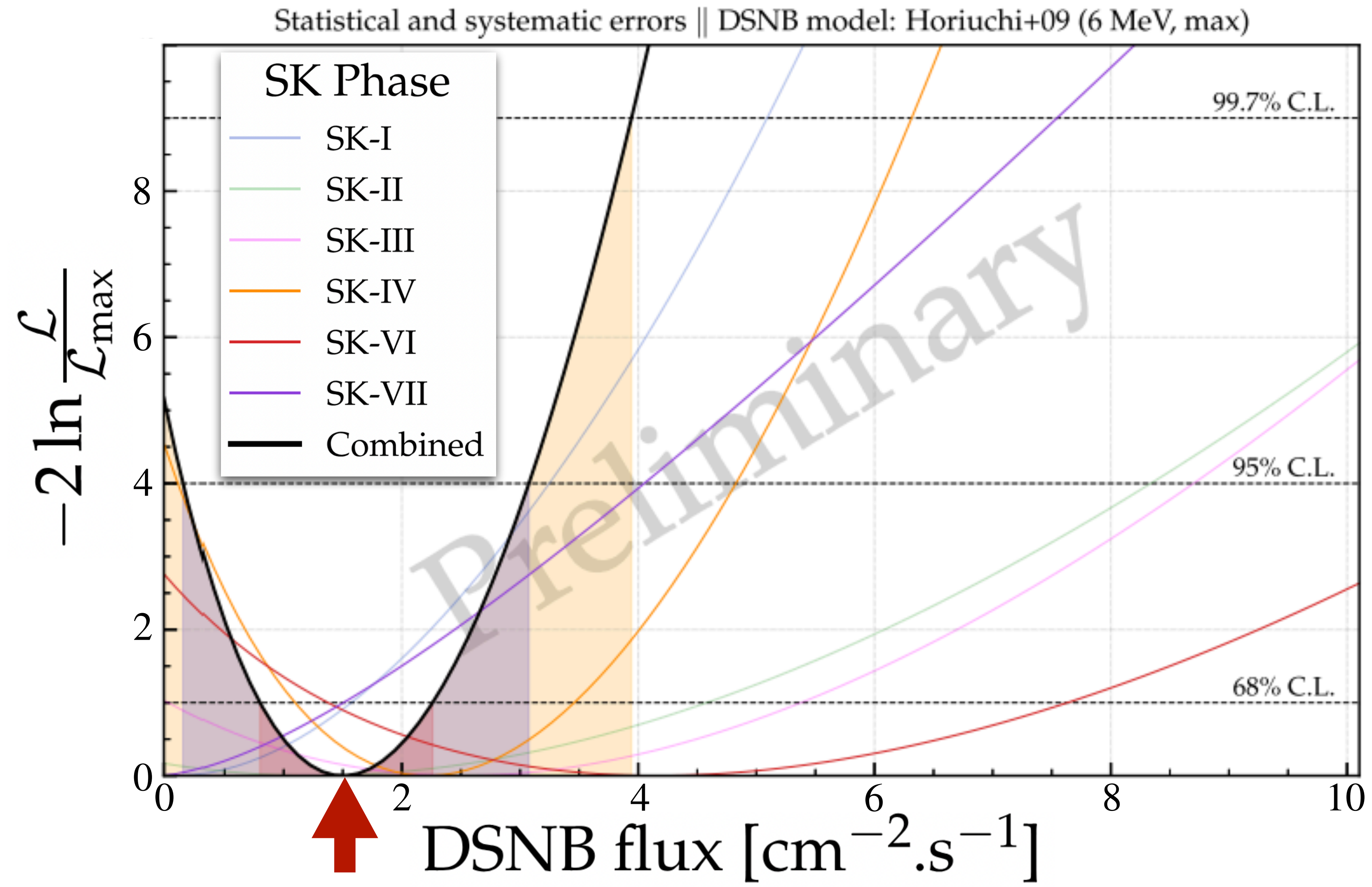
Tension from zero assumption

Spectral-fitting analysis

Spectrum fitting analysis to extract significance

- Total 6779 days of SK (5823 d pure-water and 956 d Gd-water) combined
- Analysis threshold: $E_\nu > 17.3$ MeV
- Suppress uncertainty of background prediction by fitting both N_n=1, $N_n \neq 1$





Best fit: 1.4

(Rogly, poster 79)

Highlight:

- Sensitivity of SK-Gd ~1000 days exposure is already comparable level it with ~6000 days of pure-water SK
- Best fit of whole SK observation is $1.4^{+0.8}_{-0.6}$ cm^{-2} s^{-1} for $E_\nu > 17.3$ MeV

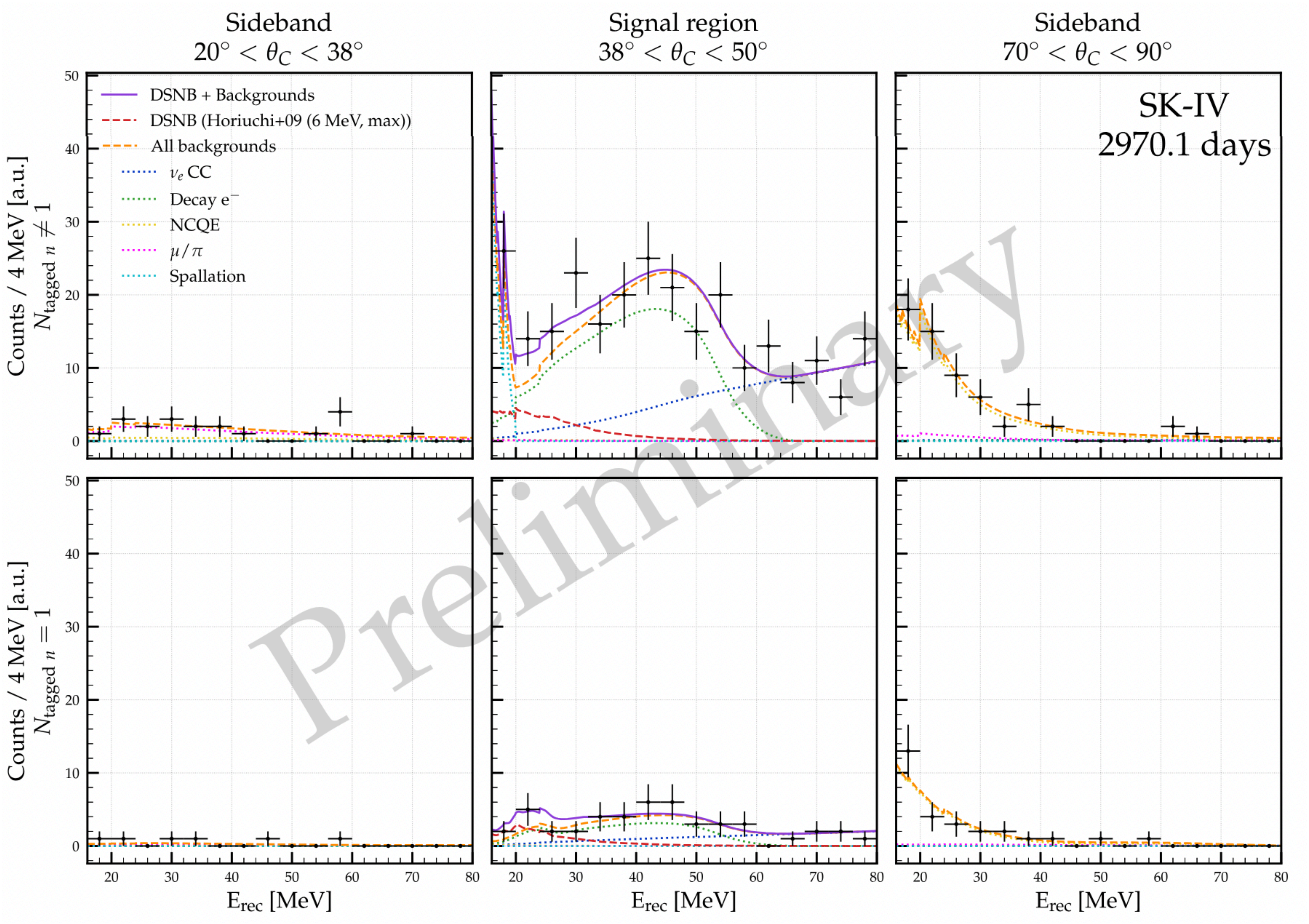
➡ exhibit ~2.3 σ excess!!

Summary

- DSNB flux keep valuable information about not only the supernova neutrino flux, but also the history of star formation and cosmic-expansion
- World wide neutrino detectors sensitive to a few tens MeV work to observe DSNB
- In recent progress, SK experiment published first result in SK-Gd era
- Also, the latest update of DSNB search in SK-Gd using additional more condensed Gd-water data are exhibited
  ➡ There is no significant DSNB signal, however, some excess appears to be visible in the signal region, which is 2.3 σ tension from non-DSNB hypothesis
- Looking forward to discovery of DSNB in the next decade !!

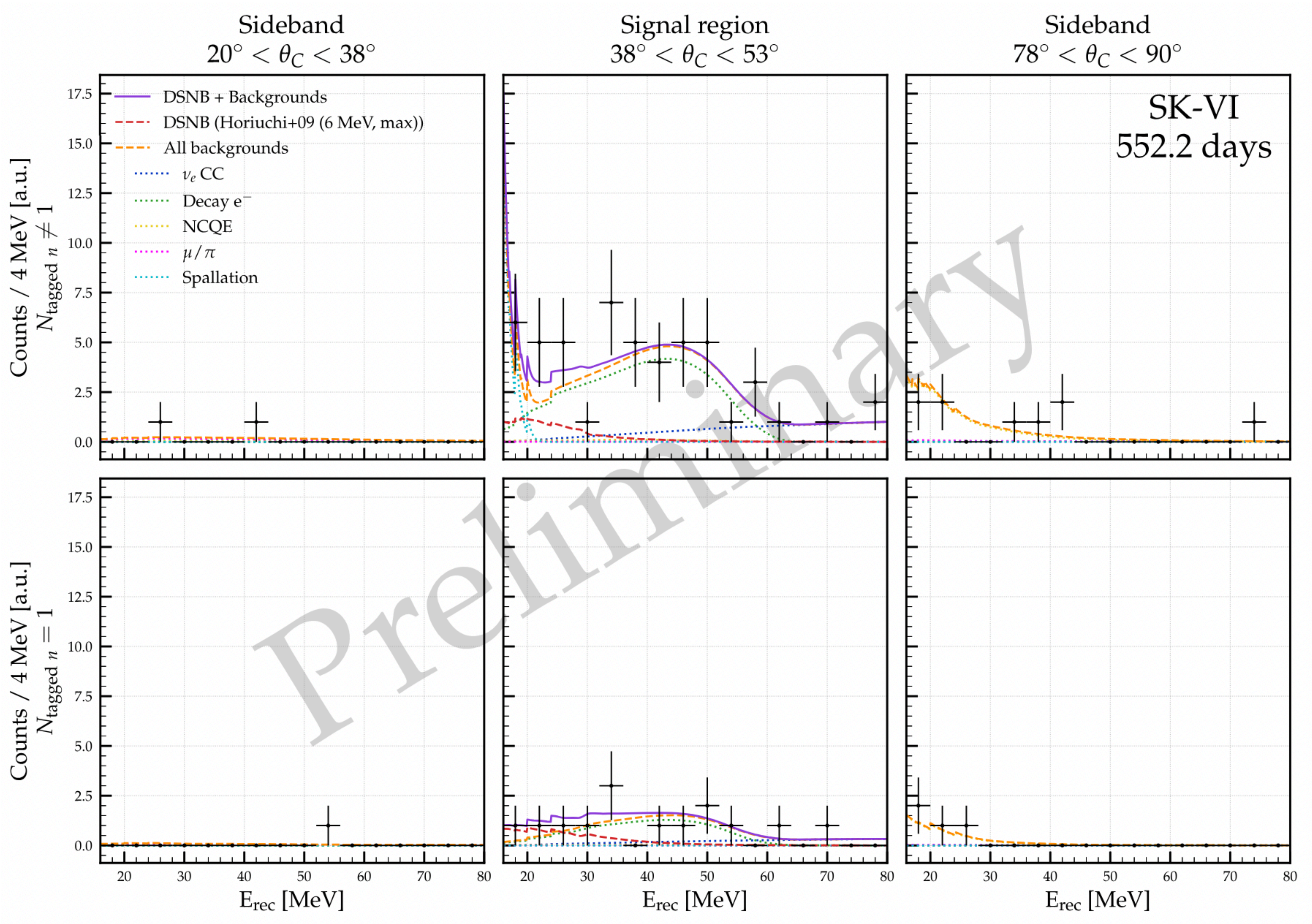
Backup

Spectrum fitting



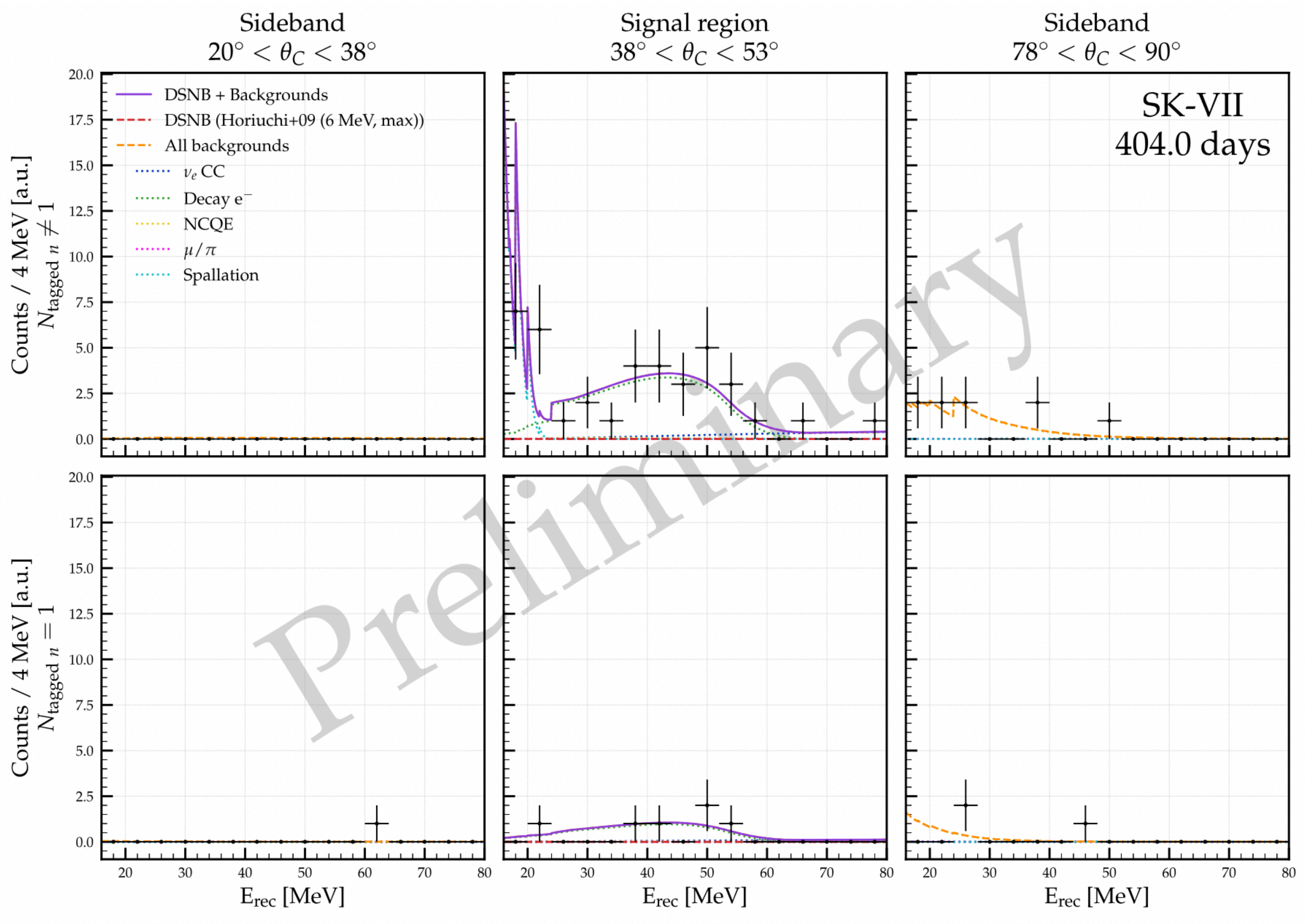
SK-IV

Spectrum fitting



SK-VI

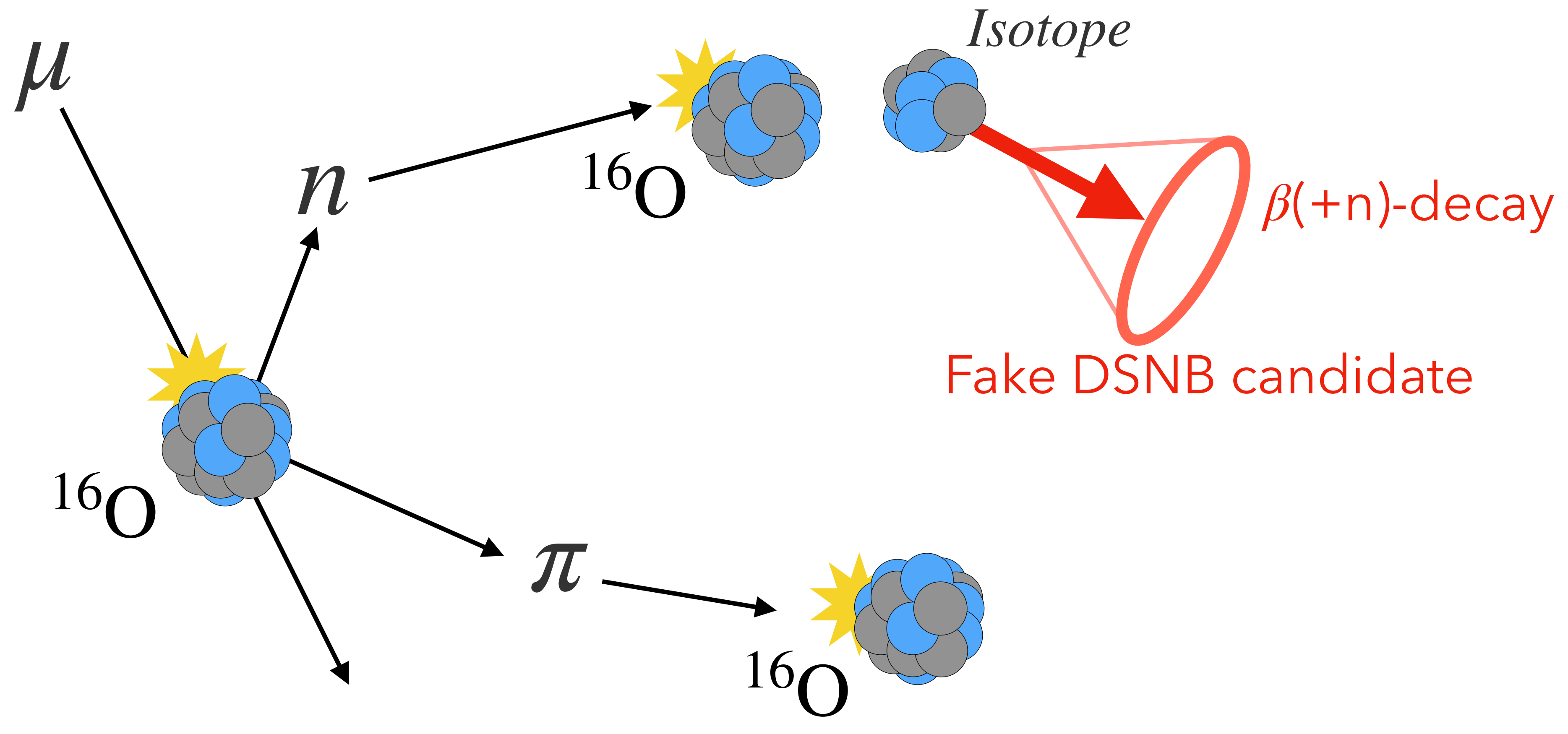
Spectrum fitting



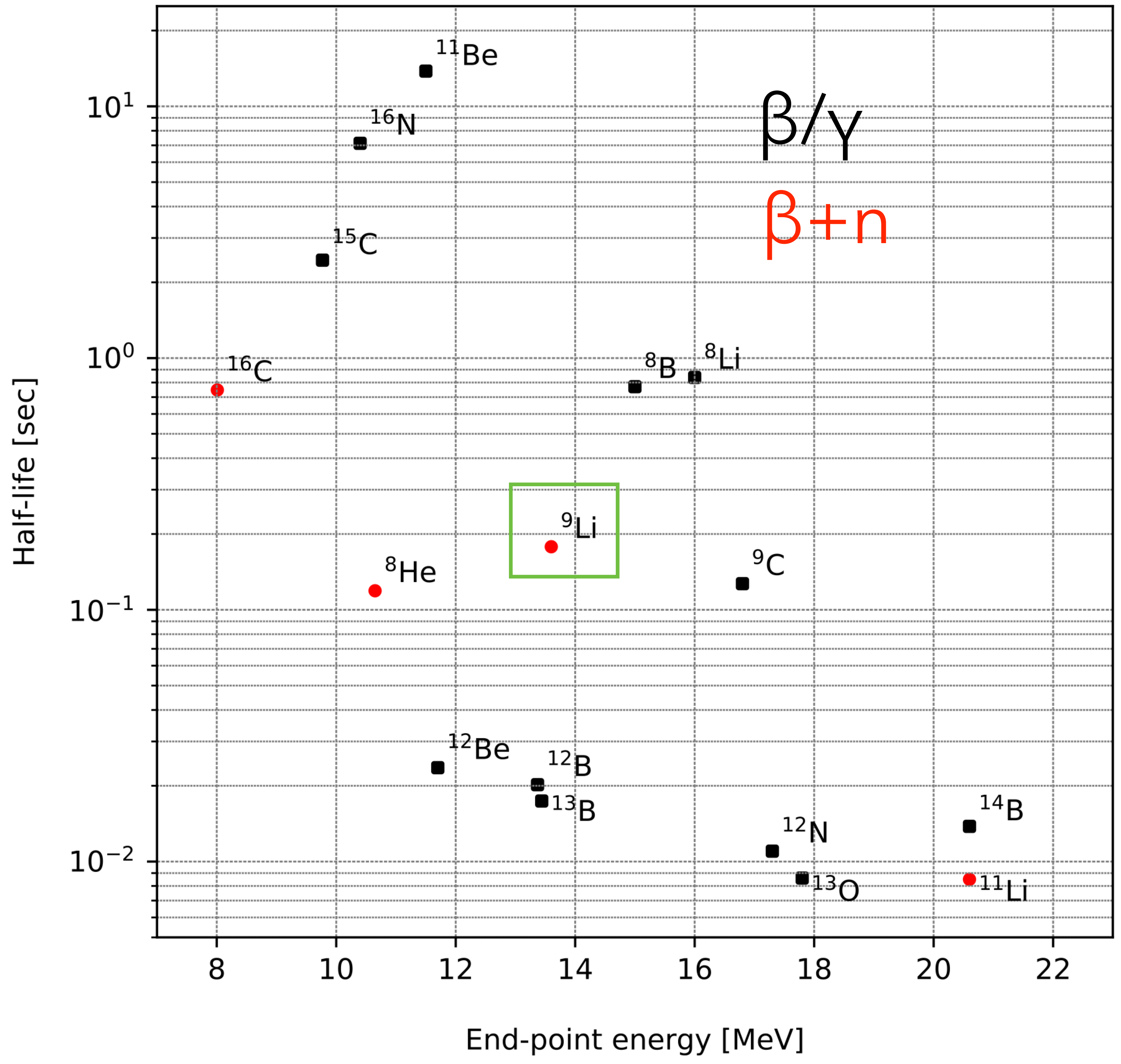
SK-VII

Background: Muon spallation products (^{9}Li)

- Cosmic-muon comes with ~2 Hz at SK site
  → Decays from broken up isotopes are fake low-energy event
  (x10^6 as DSNB rate !!)



- Lithium-9 (^{9}Li)
  - Relatively high yield, long lifetime
  - It has β + n decay branch
    →**Remaining background**

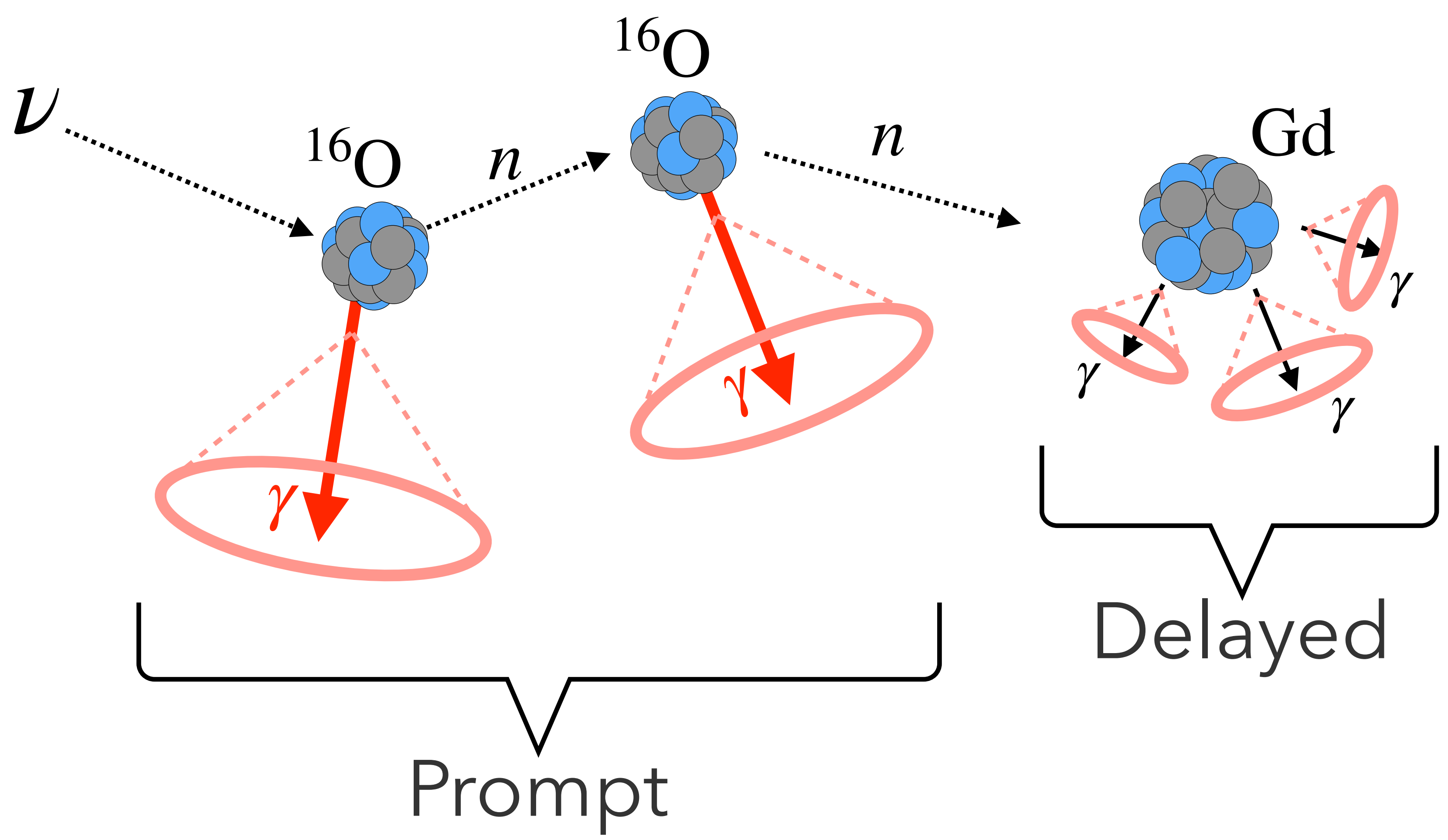


Background: Atmospheric neutrinos

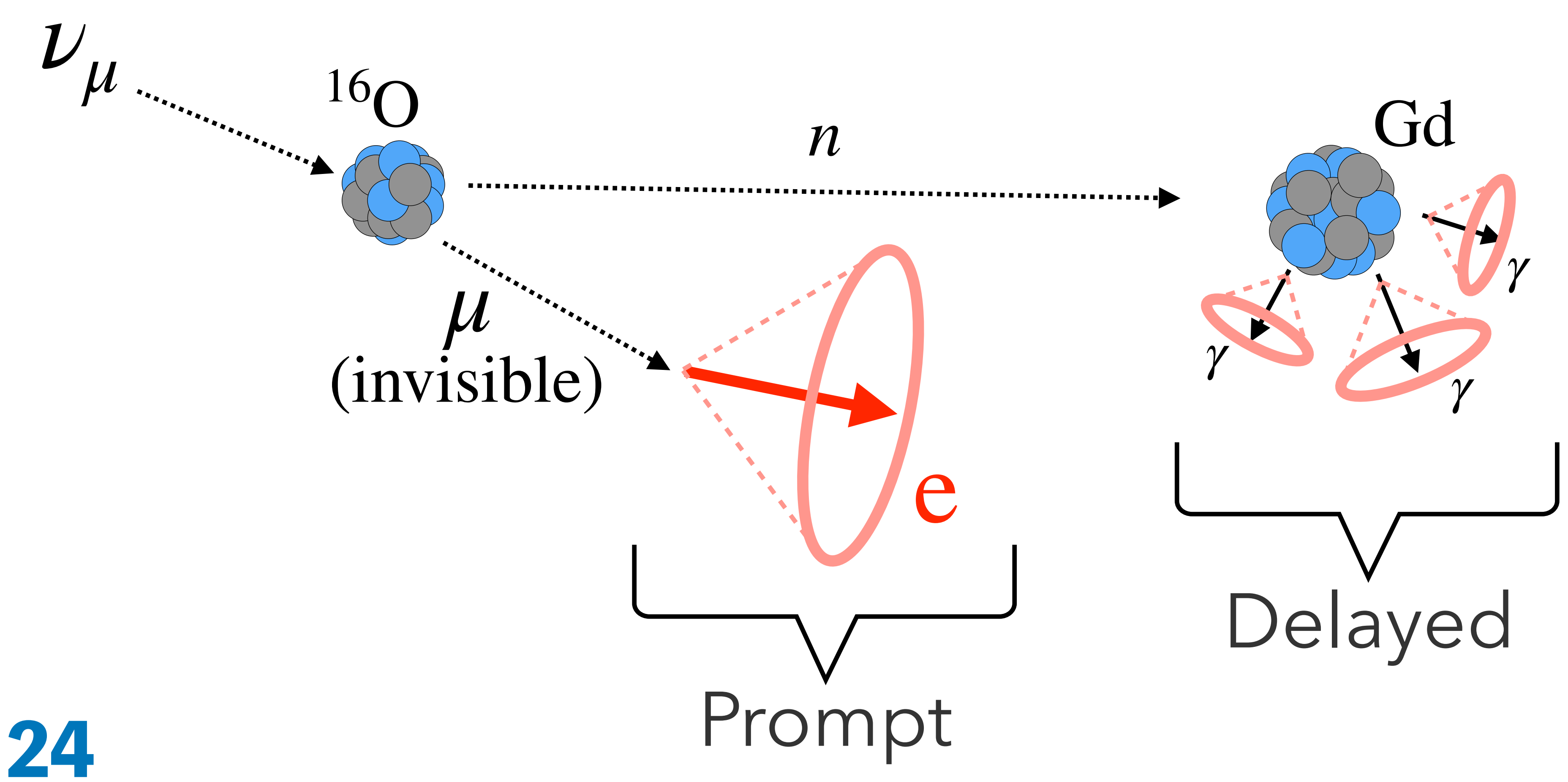
- Neutral-Current Quasi-Elastic (NCQE) interactions
    - De-excitation gamma-ray (dominant < ~20 MeV)

- non-NCQE interactions
    - Decay electron (from invisible muon) + n

NCQE



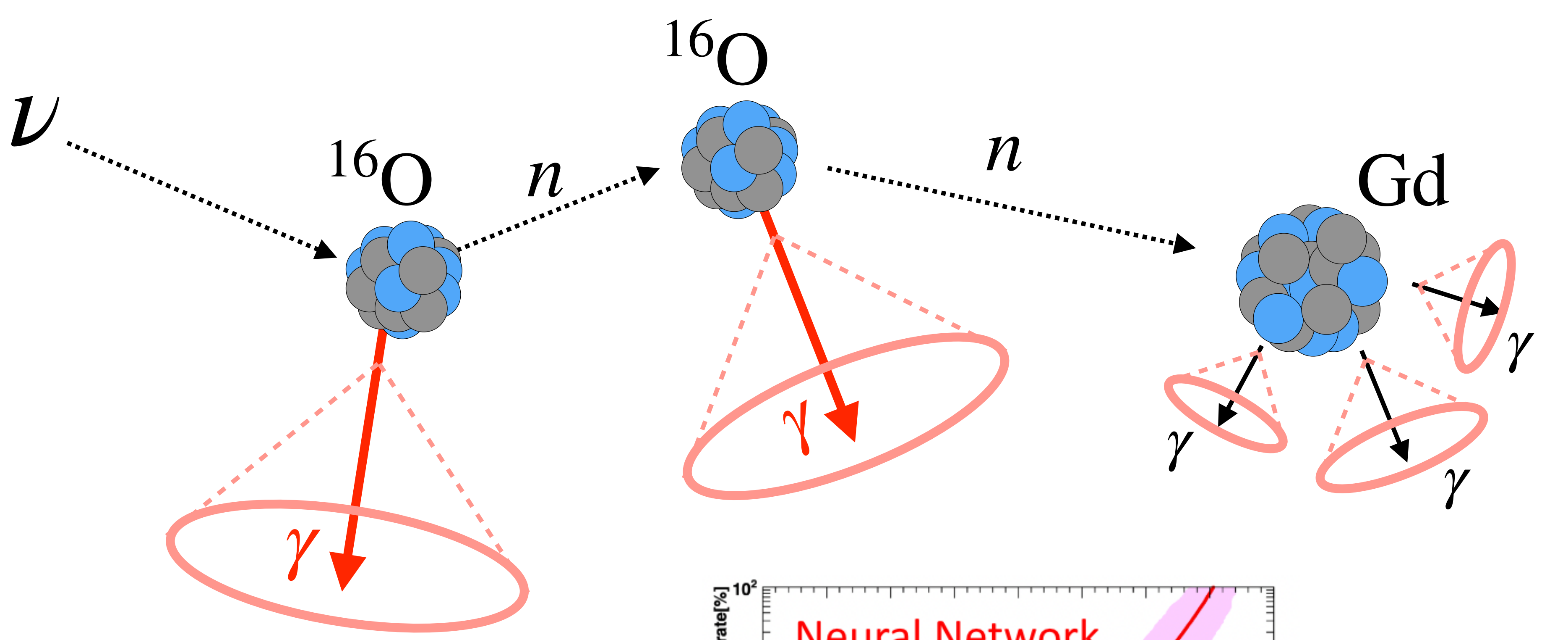
non-NCQE (CCQE)



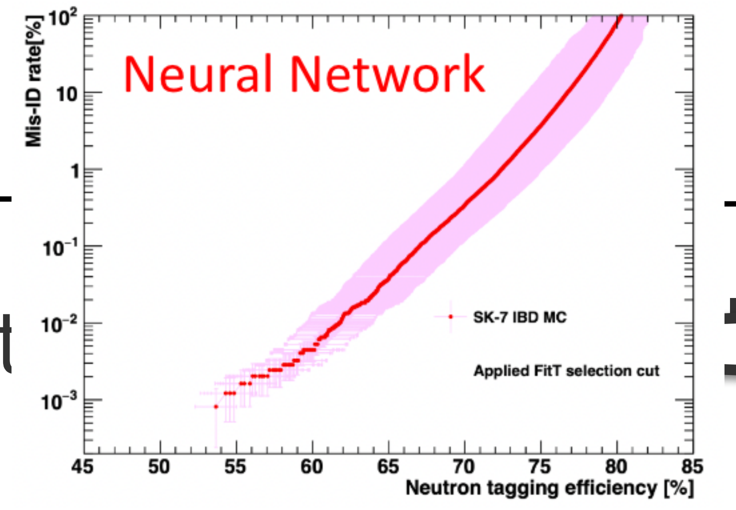
Background: NCQE event reduction

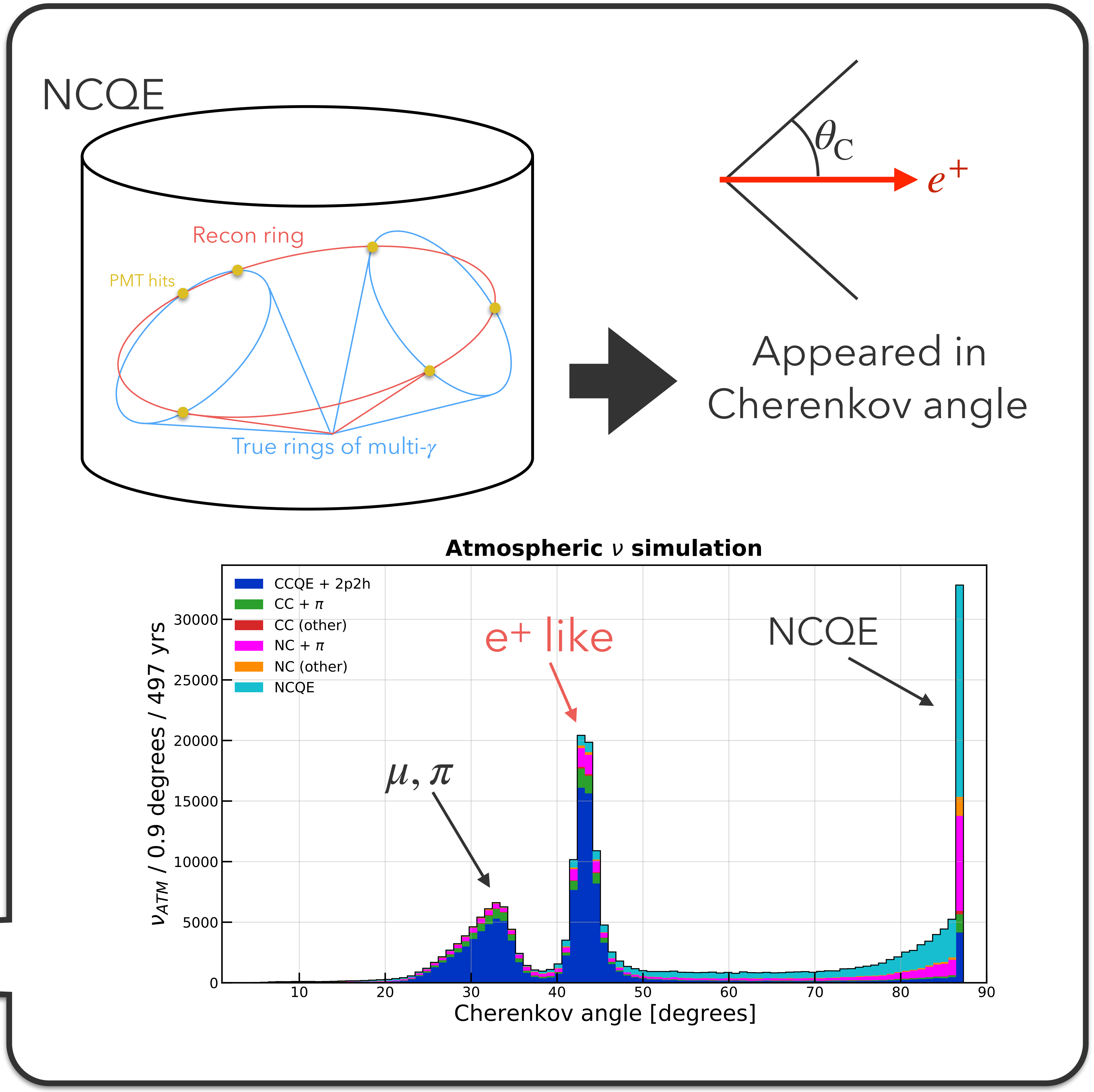
- Reduce by Cherenkov angle
  - NCQE events tend to have larger angle

NCQE



Prompt





Tagging efficiency vs mis-ID rate